Genet. Res., Camb. (1967), 9, *pp.* 211–220
Printed in Great Britain

Sex differences in recombination of linked genes in animals

BY L. C. DUNN AND DOROTHEA BENNETT‡ ||

Columbia University, Nevis Biological Station, Irvington-On-Hudson, New York, U.S.A., and Cornell University Medical College,† New York City, New York, U.S.A.*

(*Received* 26 *August* 1966)

1. INTRODUCTION

In one of Haldane's early papers (1922), he pointed out what has since come to be known as Haldane's rule: when among the offspring of crosses between species and varieties, one sex is absent, rare or sterile, it is the heterogametic sex. At the end of this paper he suggested also that 'linkage between autosomal factors is always stronger in that sex'. There were very few observations at that time on sexual differences in crossing-over. It was established that crossing-over of autosomal genes did not occur in the male (digametic) in three species of *Drosophila*, while in the silkworm moth there was no crossing over in the female (digametic). It had recently been shown that crossing-over occurs in both sexes in rats and mice, and in the case of two linked loci in rats, with lower frequency in the male, and a similar difference in mice was suggested (Dunn, 1920). Haldane, in an analysis of Nabours' (1919) data on autosomal crossing-over in the locusts Apotettix and in Paratettix (Haldane, 1920) had found similar indications of lower crossing-over frequency in the male (digametic). The above was obviously a slender basis on which to rest a 'rule' but Haldane put forward the suggestion because of its possible connexion with the first-mentioned rule, since 'the greater difficulty of fusion of chromosome pairs in the heterogametic sex might also cause its sterility'.

It is not our present purpose to assess the status of the rule concerning sex-ratio or unisexual sterility, which has continued to have many cases to support it and some exceptions. Our interest has focused rather on the fate of the other suggestion concerning sex differences in crossing-over. Is there in fact a discernible rule of this sort in animals? And whether there is or not, what light can be shed on the mechanism of crossing-over by examining the evidence on sexual variations in recombination?

It is a curious fact that not long after Haldane made his suggestion, Julian Huxley published a paper (1928) on sexual difference in linkage in the brine shrimp, *Gammarus chevreuxi*. After reporting a lower frequency of crossovers in males

Research performed under *Contract AT(30-1)1804 with the United States Atomic Energy Commission, and †USPHS Grant GM 09912.

‡ Dedicated to the memory of J. B. S. Haldane 1891–1964.

|| Career Investigator, Health Research Council of the City of New York.

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press

(digametic) of two autosomal genes, and without referring to Haldane's prior paper, Huxley also stated a rule that 'wherever crossing-over is absent or markedly reduced in one sex, that sex is the heterogametic sex. The converse does not hold; the two sexes very often have similar values for crossing-over; where the sexual difference in c.o.v. (crossover value) is slight, the rule also does not hold, e.g. Mammals.'

The situation when reviewed by Eloff in 1932 was essentially as described by Huxley (1928).

If there was to be a rule of this sort, therefore, it might more appropriately be called 'Huxley's Rule', leaving Haldane's Rule for the sex ratio and sterility differences in varietal and species crosses. Some clarification would be needed, in any case, since in a recent paper Sokoloff (1964), in reporting some significant sexual differences in the flour beetle, *Tribolium castaneum*, says: '...the data to be presented violate Haldane's (1922) rule that crossing-over is reduced or prevented in the heterogametic sex.' As we shall see, however, the evidence published since Haldane and Huxley wrote does not support any consistent rule relating sexual differences in recombination frequency to heterogamety.

It should be pointed out before examining the detailed evidence that ideas about two situations which may be qualitatively different were included within each of the statements concerning sex and crossing-over. One referred to the failure of recombination of linked autosomal genes in one sex, as in the male of *Drosophila* species and in the female silkworm moth. The other referred to quantitative differences in the recombination fraction in those cases now known to constitute the great majority, in which crossing-over occurs in both sexes. After discussing both of these ideas it was concluded, before Haldane or Huxley had formulated a rule (Dunn, 1920), 'The fact remains that no crossing-over or less crossing-over in the autosomes cannot be explained by reference to the sex chromosome alone.' It is proposed now to assess the present state of these two ideas.

In respect to the absence of recombination in one sex, this has turned out to be an anomaly found only in a few insect families. It is surprising for how few animal species such information exists, requiring as it does identification of autosomal linkage groups as well as of sex chromosome constitution. The *Drosophila* species continue to agree with *melanogaster* in virtual absence of autosomal crossing-over in the male. It has been well established in one other dipteran genus by Bauer's (1946) observations on *Phryne fenestralis* which also, like *Drosophila*, forms no chiasmata in spermatocytes. In the few cases known, the sex in which crossing-over is absent or rare is the heterogametic sex.

The more general case is that in which recombination occurs in both sexes. Since Haldane wrote, the chief additions to data on comparative recombination of linked genes in the two sexes have come from mammals, especially the house mouse, from the domestic fowl and most recently from the flour-beetle *Tribolium*. One well-studied case in the fowl (Landauer, 1933; Fisher & Landauer, 1953) shows conclusively that in one short segment, at least, recombination is significantly *greater* in the heterogametic sex (female). Warren (1940) found no evidence of sex

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press

difference in four other linkages. In the pigeon three loci in one linkage group show more recombination in the male but the data are quite limited (Hollander, 1938). In the rabbit two loci in one linkage group and in the rat three linked loci show somewhat more recombination in females (homogametic) but the data as a whole are insufficient to support any rule (Castle, 1936). The best data come from the mouse as reviewed by Michie (1955) and brought up to date for this paper, and from *Tribolium* (Sokoloff, 1964). The latter case shows decisively that for one region comprising four loci in the seventh linkage group, recombination is much *higher* in the heterogametic sex (male).

The data for the mouse are extensive and will be discussed in more detail. The observations available for comparison between the sexes are given in Table 1. In examining this table, it should be borne in mind that a number of variables such as temperature and age are known to influence crossing-over and that these have not usually been controlled in experiments on linkage in mice. Bodmer (1961), for example, showed that in one region of the fifth linkage group, there was a significant decrease with age in the recombination fraction in females, but not in males: Reid & Parsons (1963) similarly found that recombination tended to vary with age more in females than in males. Thus only those differences between the sexes which are large and consistent are likely to be significant.

The observations summarized in Table 1 show that evidence for making judgments is available for fifty-four intervals in thirteen linkage groups. Of these two-point recombination tests, thirty indicate no significant differences between males and females. In twenty-four intervals a sex difference having a p value of 0·05 or less was found. In nineteen of these, the recombination percentage was higher in females; in five it was higher in males. The higher female rate was found in ten linkage groups, the higher male rate chiefly in one linkage group, with one case in one other group.

The cases in which a difference occurs show no obvious relation to the length of interval, although the closest linkages (e.g. *d–se* in II and *Ki–tf* in IX) which rest on large numbers of observations do not show significant sex differences. The relation between sex differences in recombination and physical features of the chromosome, such as location of centromere or heterochromatin, cannot be determined directly and inferences based on interference or centromere heterogeneity (affinity) are too indirect to be useful in this connexion.

One fact disclosed by Table 1 is however quite suggestive. In linkage group VI all of the significant differences are in the direction opposite to that prevailing in other linkage groups. In these data, largely due to W. F. Hollander, the heterogametic sex (male) shows more rather than less crossing-over. The observations in this case are extensive, the differences are large, and those by different observers agree.

This situation in linkage group VI contrasts strongly with that in one segment of linkage group IX of which we have made a special study. The region analyzed is that between the markers *T* (short tail or Brachyury) and *tf* (tufted hair-loss pattern). Many other mutants called collectively *t*-alleles (since they show no

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press

Table 1. *Comparison between males and females in recombination of linked genes in the house mouse. Data not otherwise attributed are from Michie*, 1955 (*Table* 10). *Percentages in significant excess* (p = 0·05) *are in bold type*

Linkage group	Interval	Recombination (%) In females	Recombination (%) In males	*P*	Reference
I	*sh–1–fr*	15·8 ± 3·7	19·4 ± 6·6	> 0·5	
	hb–c	**7·3 ± 0·8**	3·5 ± 0·8	0·003	Popp & St. Amand, 1964
	sh–1–c	4·1 ± 0·4	3·0 ± 0·5	~ 0·1	
	c–p	**16·0 ± 0·5**	12·2 ± 0·5	$< 10^{-6}$	
II	*lu–Trf*	23·8 ± 5·3	20·7 ± 5·2	> 0·5	Shreffler, 1963
	d–se	0·14 ± 0·02	0·17 ± 0·03	0·3	Goodwins & Vincent, 1955
	d–se	0·11 ± 0·02	0·39 ± 0·39	> 0·5	
	d–Trf	**21·4 ± 3·3**	9·8 ± 2·8	0·007	Shreffler, 1963
III	*s–hr*	**9·8 ± 2·1**	2·4 ± 2·4	0·02	
V	*Ra–a*	20·6 ± 1·4	23·4 ± 1·5	0·19	Parsons, 1958
	Ra–a	20·0 ± 1·8	21·2 ± 2·1	0·3	Lane & Green, 1960
	Ra–we	32·7 ± 1·6	33·3 ± 1·7	0·5	Parsons, 1958
	a–un	4·7 ± 0·4	4·6 ± 0·4	0·8	
	a–we	**17·5 ± 1·2**	10·5 ± 1·1	10^{-4}	
	a–we	13·9 ± 1·2	11·1 ± 1·1	0·07	Parsons, 1958
	a–mg	**12·8 ± 1·0**	9·8 ± 1·1	0·05	Lane & Green, 1960
	a–pa	21·2 ± 2·7	19·6 ± 2·6	0·5	
	a–fi	**35·8 ± 2·0**	27·1 ± 1·9	0·003	Wallace, 1957
	un–we	**7·4 ± 0·5**	4·4 ± 0·4	10^{-5}	
	we–pa	**4·2 ± 0·4**	2·2 ± 0·3	10^{-4}	
	pa–fi	27·4 ± 1·6	26·6 ± 4·4	0·5	Bodmer, 1961
	fi–Sd	20·6 ± 1·7	24·0 ± 1·8	0·16	Wallace, 1957
VI	*N–Ca*	1·5 ± 0·6	2·7 ± 0·6	0·16	Mallyon, 1951
	N–Ca	0	**3·1 ± 0·9**	0·05	
	N–Ca	0·3 ± 0·1	**1·3 ± 0·2**	10^{-6}	Hollander, 1966
	Ca–hl	1·4 ± 0·2	**4·9 ± 0·5**	10^{-6}	Hollander, 1966
	Ca–Ht	1·6 ± 1·6	6·6 ± 3·3	0·1–0·2	St. Amand & Cupp, 1957
	Ca–bt	3·8 ± 1·0	**11·1 ± 1·2**	10^{-6}	Mallyon, 1951
	Ca–bt	9·4 ± 2·4	13·8 ± 2·9	0·2	Mallyon, 1951
	N–bt	4·3 ± 0·5	**13·0 ± 0·7**	10^{-7}	Hollander, 1966
	hl–bt	7·6 ± 0·6	8·6 ± 0·7	0·3	Hollander, 1966
VII	*Re–ti*	19·5 ± 2·1	20·9 ± 2·2	> 0·5	Searle, 1961
	Re–vt	**27·6 ± 3·1**	18·0 ± 3·2	0·02	
	Re–sh–2	21·7 ± 8·6	19·2 ± 1·7	0·7	
	re–wa–2	42·2 ± 2·4	43·6 ± 2·5	> 0·5	
	sh–2–wa–2	23·6 ± 0·9	**29·5 ± 1·4**	< 0·001	
VIII	*m–Pt*	3·9 ± 0·6	2·2 ± 1·5	0·27	Lane, 1963
	m–b	7·1 ± 1·1	8·2 ± 3·5	> 0·7	
	Pt–b	5·4 ± 1·5	4·9 ± 1·1	> 0·7	
	Pt–b	5·3 ± 1·1	5·2 ± 0·5	> 0·5	Lane, 1963
	b–wi	**6·0 ± 0·7**	2·5 ± 0·7	0·00008	Lane, 1963
IX	*H–2–T*	**15·4 ± 1·1**	8·3 ± 0·7	0·00006	Allen, 1955
	tf–Ki	0·0115 ± 0·0046	0·0037 ± 0·0026	0·13	Dunn *et al.*, 1962
	tf–T	**9·1 ± 1·0**	6·7 ± 0·8	0·05	Lyon, 1965

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press

Table 1—*continued.*

Linkage group	Interval	Recombination (%) In females	In males	P	Reference
	Ki–T	5·9	2·5	0·04	
	T–Fu	0·0	4·3	~ 0·2	
	Ki–Fu	3·6	0·0	0·1	
XI	*mi–wa*–1	8·7 ± 2·0	9·4 ± 3·6	> 0·8	
	mi–wa–1	3·2 ± 1·4	4·2 ± 1·5	> 0·5	Phillips, 1960
	wa–1–*Lc*	8·5 ± 2·0	7·8 ± 1·9	> 0·5	Phillips, 1960
XIII	*Lp–ln*	38·1 ± 7·7	35·1 ± 3·6	0·7	
	py–ln	**40·3 ± 1·8**	23·0 ± 2·0	$< 10^{-7}$	
	th–ln	2·6 ± 0·7	1·3 ± 0·7	0·19	Russell, 1965
	ln–Sp	8·5 ± 3·8	5·8 ± 2·8	> 0·2	
	ln–Sp	5·8 ± 1·4	4·1 ± 1·0	0·3	Dickie, 1964
	ln–Sp	4·0 ± 0·9	3·2 ± 1·0	> 0·5	Russell, 1965
	ln–fz	49·2 ± 4·0	39·1 ± 4·1	0·07	Dickie & Woolley, 1950
	Sp–fz	**39·8 ± 3·8**	31·6 ± 2·8	0·05	
	Sp–fz	38·9 ± 2·8	31·3 ± 2·4	0·05	Dickie, 1964
XIV	*pe–Xt*	**42·5 ± 4·8**	27·1 ± 3·8	0·01	Lyon, 1965
	f–Xt	32·1 ± 4·0	25·9 ± 3·7	0·20	Lyon, 1965
XVII	W^v–*pi*	5·3 ± 2·3	11·4 ± 2·9*	0·1	
	W^v–*lx*	17·5 ± 2·3	18·9 ± 2·0	0·5	
XVIII	*Os–Hk*	**18·2 ± 2·4**	7·6 ± 2·8	0·005	Green *et al.*, 1963

* This figure is given incorrectly in Michie's (1955) paper as 8·8 ± 2·7.

recombination with *T*) have been localized in this same region (Dunn, Bennett & Beasley, 1962). Some of these alleles are lethals and of six of these studied, five suppress all regular recombination between *T* and *tf*; one permits nearly a normal amount of females. Other *t*-alleles are viable when homozygous. Lyon & Meredith (1964) tested the effect on recombination of ten such viable alleles derived from one lethal, t^6. All gave recombination fractions in males which were lower than standard, in five cases very significantly so. Recombination in females did not differ significantly from the standard. We tested this effect in nineteen viable alleles, each derived from a different exceptional gamete produced by one of six different balanced lethal lines. Our results were almost the same as Lyon and Meredith's. The seven cases showing recombination values in male heterozygotes which differed significantly from standard ($p = 0·05$ or less) all had low values. In no case did the value in females differ significantly from standard. Table 2 lists these data. In addition, one test of the only lethal allele which permits recombination ($t^{w18} = t^9$) is also shown, based on unpublished data by Phebe Van Valen. This conforms to the same pattern, the male value being lower.

It is clear from this table that when the recombination fraction in the presence of a *t*-allele differs from the standard value it is always the male value which is depressed. This supports the conclusion, derived from the suppression of recombination by *t*-alleles, that the effect of such alleles extends over the interval from *T* to *tf*, covering some nine recombination units in linkage group IX. If the lowered

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press

Table 2. *Effect of* t-*alleles which permit some recombination on recombination in* T–tf *interval*

Allele	Recombination fraction in male heterozygotes	In females	Difference from standard (p value)
Standard	6·74 ± 0·76	9·12 + 0·97	0·05 (difference ♀–♂)
t^{13} viable	1·13 ± 0·78		0·00006
t^{28} viable	2·43 ± 1·06		0·003
t^{29} viable	2·66 ± 1·19		0·004
t^{w35} viable	3·15 ± 1·10		0·007
t^{w57} viable	3·54 ± 1·17		0·02
t^{w58} viable	3·41 ± 1·30		0·03
t^{w59}	3·06 ± 1·70		0·05
*10 viables; t^{h2}–t^{h21}	3·46 ± 0·41		0·05
†t^{w18}–t^{w9} (lethal)	4·01 ± 0·85		0·02

* From Lyon & Meredith, 1964.
† From P. Van Valen, in MSS.

recombination due to a *t*-allele is associated with lowered probability of effective pairing or of chiasma formation in one region of chromosome IX, and if this affects spermatogenesis rather than oögenesis, then sexual differences in recombination may reflect different probabilities of such events in the two sexes. There is at present no direct evidence of this but at least there is a suggestion of what to look for.

The chief interest at the moment in the peculiar contrast between a segment in linkage group IX and one in linkage group VI lies in the indication that differences in recombination probability are affected by local factors. It warns us too that such local differences in one linkage group may not be characteristic of the species genome as a whole. Sokoloff (1964) has pointed this out in showing that in *Tribolium castaneum* the lower frequency of recombination in females which occurs in linkage group VII does not occur in IV and V.

2. DISCUSSION

It is apparent from what has been said above that in respect to animals in which recombination occurs in both sexes, there is no simple rule of the sort suggested by Haldane. Huxley was aware that such a rule failed to hold in cases where the sexual difference in crossing-over frequency is slight as in mammals. But now the crossover value can be seen to vary widely and in both directions in the same species, e.g. mice and *Tribolium*, and to vary in opposite ways in two species, e.g. the domestic fowl and the pigeon, in both of which the female is digametic. It may still be true that in mammals generally, as in the mouse, recombination of linked genes is likely to be more frequent in the female and may be more subject to reduction in the male by chromosomal aberrations. There may well be factors with general effects on recombination throughout the nucleus. Such for example is the case with the autosomal gene C3g in *Drosophila melanogaster* which the Gowens (1922) showed to

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press

suppress recombination throughout the genome in females. The opposite effect, enhancement of recombination in one chromosome when it is prevented in others by the presence of inversions, is also known in *Drosophila* females as well as effects of temperature, age and some other variables. There is no inherent improbability in the existence of forces acting between chromosomes or in the nucleus as a whole to influence the general probability of crossing-over between homologous chromosomes. There might even be an enzyme which, if present, causes pairing to be effective and to result in crossing-over, while if absent (as for example in the Gowens' case) pairing or crossing-over may fail to occur at all. But if such were to be the mechanism by which in mammals (for example) chromosomes are generally more likely to undergo crossing-over in the female, it would be subject to severe limitations due to the reversal of the usual effect in certain chromosome regions, as shown by results from mice and *Tribolium*.

Similarly, there may be differences between males and females in intensity of interference. Such a difference was posited by Parsons (1958) for a long segment of linkage group XIII. These would in general not affect adjacent loci between which double crossing-over would be unlikely to occur. Although the two closest linkages (*d–se*) and (*Ki–tf*) do not show a sex difference, other short intervals do (*we–pa*; *N–Ca*). This has already been pointed out by Fisher & Landauer (1953) for both mouse and fowl. Again too little is known about the distribution of interference in the linkage groups of the mouse to support much speculation on this.

It seems to us that, on the whole, the exploration of local differences in recombination holds more promise of elucidating the mechanism of the influence of sex on recombination frequency than the reverse, e.g. the alteration of the sexual state in an attempt to elucidate local differences. Yamamoto (1961) has carried out an interesting experiment by the latter method. In the Medaka (*Oryzias latipes*), fish of XY chromosome constitution, which are normally males, may by hormone treatment be caused to become functional XY females. In such induced XY females, crossing-over between X^r and Y^R, as tested by normal males X^RY^R, occurs at about five times the frequency with which it occurs in males. Yamamoto concluded that the difference in crossing-over in this case 'depends not on heterogamety as such but on other cytological conditions associated with sex'. We agree with this view.

There is some direct evidence that failure of recombination in the males of some dipteran species (*Drosophila*; *Phryne*) is associated with absence of chiasmata in spermatogenesis although they do occur in oögenesis. The opposite situation obtains in *Bombyx* and *Galleria* in which no recombination and no chiasmata occur in oögenesis.

Suomalainen (1965) has shown that in more than forty species of the geometrid moth genus *Cidaria*, no chiasmata appear in oögenesis. Suomalainen assumes that recombination does not occur in females of these species although genetical evidence is not available. He makes the interesting suggestion that the large number and small sizes of the chromosomes in the Lepidoptera 'is a means for compensating for this (i.e. lack of recombination) and is perhaps partly explained just by this condition'. A suggestion arising from Henderson's (1961) study of chromosomes in the

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press

locust family Tetrigidae was that lower crossing-over in male locusts, as discovered by Nabours (1919), is associated with absence of chiasmata in Apotettix and with localization of chiasmata in Paratettix.

Although the 'rules' of Haldane and of Huxley were intended to apply only to animals with separate sexes, what may be the best clue to understanding sex differences in crossing-over has come from studies on crossing-over in hermaphroditic plants, especially in maize. The reproductive mechanism in such plants is obviously not comparable to that in, for example, mammals, yet Rhoades (1941), in a thorough analysis of the distribution of crossovers in one chromosome of maize, has disclosed a situation resembling somewhat that in mice. Crossing-over in maize occurs in both the production of pollen (microsporogenesis) and in the production of ovules (megasporogenesis). Rhoades proved that a marked difference in frequency of crossing-over between the two types of gametes is confined to those regions close to the centromere in chromosome 5. These regions are heteropycnotic, and Rhoades suggested that crossing-over may be reduced in such regions. 'It is possible that in microsporocytes a lesser degree of pycnosis occurs in the proximal parts than in megasporocytes and that this is reflected in a higher crossover frequency in the male flowers.' The sex difference in crossing-over in heterochromatin may reflect environmental differences between the male and female flowers. The essential feature of Rhoades' hypothesis is that sex differences in crossing-over are caused by localized differences in the probability of chiasma formation due to the state of the chromatin. Other localized sexual differences in recombination frequencies had been noted in *Primula* by De Winton & Haldane (1935).

Westergaard (1964) has recently suggested that 'allelic crossing-over due to a replication mechanism may be possible in loci which are close to heterochromatic segments'. This means that allelic crossing-over in higher plants and animals would be confined to certain loci. Although the crossing-over studied by Rhoades was probably normal inter-allelic recombination and thus associated with chiasma formation rather than replication, it is nevertheless of interest to find repeated suggestions of localization of recombination ascribed to nearness to heterochromatin.

Whether similar hypotheses can be applied to the localization of sexual difference in recombination as between the ninth and sixth linkage groups in mice, for example, cannot be decided at present. At the least, a study of heterochromatin quantity and localization in spermatogenesis and oögenesis in mammals seems desirable. Also, although there is some indication of sexual differences in chiasma frequency in the mouse (Crew & Koller, 1932) this was an overall average favoring the female and thus not competent to explain sex differences in opposite direction in recombination in different chromosomes.

SUMMARY

Reports of sex differences in crossing-over in animals, published since Haldane in 1922 suggested that crossing-over should be less frequent in the heterogametic sex, have been reviewed and discussed. No general rule is discernible apart from the

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press

absence of crossing-over in males of the dipteran genera *Drosophila* and *Phryne* and in females of some lepidopteran species, due apparently to failure of chiasma formation in the heterogametic sex. In the majority of animal species examined crossing-over occurs in both sexes. While there is some tendency in mammals for crossover values in females to exceed those in males, it was of greater interest to find that marked sex-differences occur in the same species (data chiefly from the house mouse) in opposite directions in different chromosomes. The influence of factors acting locally in the chromosomes, such as those associated with heterochromatin, were indicated as promising subjects for the study of variations associated with sex.

REFERENCES

Allen, S. L. (1955). Linkage relations of the genes Histocompatibility-2 and Fused tail, brachyury and Kinky tail in the mouse, as determined by tumor transplantation. *Genetics*, **40**, 627–650.

Bauer, H. (1946). Gekoppelte Verebung bei *Phryne fenestralis* und die Beziehung zwischen Faktorenanstausch und Chiasmabildung. *Biol. Zbl.* **65**, 108.

Bodmer, W. F. (1961). Viability effects and recombination differences in a linkage test with pallid and fidget in the house mouse. *Heredity, Lond.* **16**, 485–495.

Castle, W. E. (1936). Further data on linkage in rabbits. *Proc. natn. Acad. Sci. U.S.A.* **22**, 222–225.

Dickie, M. M. (1964). New splotch alleles in the mouse. *J. Hered.* **55**, 97–101.

Dickie, M. M. & Woolley, G. W. (1950). Fuzzy mice. *J. Hered.* **41**, 193–196.

Dunn, L. C. (1920). Linkage in mice and rats. *Genetics*, **5**, 325–343.

Dunn, L. C., Bennett, D. & Beasley, A. B. (1962). Mutation and recombination in the vicinity of a complex gene. *Genetics*, **47**, 285–303.

Eloff, G. (1932). A theoretical and experimental study on the changes in the crossing-over value, their causes and meaning. *Genetica*, **14**, 1–116.

Fisher, R. A. & Landauer, W. (1953). Sex differences of crossing-over in close linkage. *Am. Nat.* **87**, 116.

Goodwins, I. R. & Vincent, M. A. C. (1955). Further data on linkage between short ear and maltese dilution in the house mouse. *Heredity, Lond.* **9**, 413–414.

Gowen, M. S. & Gowen, J. W. (1922). Complete linkage in *Drosophila melanogaster*. *Am. Nat.* **56**, 286–288.

Green, M. C., Snell, G. D. & Lane, P. W. (1963). Linkage group XVIII of the mouse. *J. Hered.* **54**, 245–247.

Haldane, J. B. S. (1920). Note on a case of linkage in Paratettix. *J. Genet.* **10**, 47–51.

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

Henderson, S. A. (1961). The chromosomes of British Tetrigidae (Orthoptera). *Chromosoma*, **12**, 553–572.

Hollander, W. F. (1938). A sex difference in linkage intensity of three autosomal factors in the domestic pigeon. *Genetics*, **23**, 24–27.

Hollander, W. F. (1966). Private communication.

Huxley, J. S. (1928). Sexual difference of linkage in *Gammarus chevreuxi*. *J. Genet.* **20**, 145–156.

Landauer, W. (1933). Creeper and single comb linkage in fowl. *Nature, Lond.* **132**, 606.

Lane, P. W. (1963). Whirler mice; a recessive behaviour mutation in linkage group VIII. *J. Hered.* **54**, 263–266.

Lane, P. W. & Green, M. C. (1960). Mahogany, a recessive color mutation in linkage group V of the house mouse. *J. Hered.* **51**, 228–230.

Lyon, Mary F. (1965). Private communication in *Mouse News Lett.* **32**, 39.

Lyon, Mary F. & R. Meredith (1964) Investigations of the nature of *t*-alleles in the mouse. I. Genetic Analysis of a series of mutants derived from a lethal allele. *Heredity* 19:301–312.

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press

Mallyon, S. A. (1951). A pronounced sex difference in recombination values in the sixth chromosome of the house mouse. *Nature, Lond.* **168,** 118–119.

Michie, Donald (1955). Genetical studies with 'vestigial tail' mice. I. The sex difference in crossing-over between vestigial and Rex. *J. Genet.* **53,** 270–279.

Nabours, Robert K. (1919). Parthenogenesis and crossing over in the grouse locust Apotettix. *Am. Nat.* **53,** 131–142.

Parsons, P. A. (1958). Additional three-point data for linkage group V of the mouse. *Heredity, Lond.* **12,** 357–362.

Phillips, R. J. S. (1960). Lurcher, a new gene in linkage group XI of the house mouse. *J. Genet.* **57,** 35–42.

Popp, R. A. & St. Amand, W. (1964). A sex difference in recombination frequency in the albinism-hemoglobin interval of linkage group I in the mouse. *J. Hered.* **55,** 101–103.

Reid, D. H. & Parsons, P. A. (1963). Sex of parent and variation of recombination with age in the mouse. *Heredity, Lond.* **18,** 107–108.

Rhoades, M. M. (1941). Different rates of crossing over in male and female gametes of maize. *J. Am. Soc. Agron.* **33,** 603–615.

Russell, L. B. (1965). Private communication in *Mouse News Lett.* **33,** 69.

St. Arnand, W. & M. B. Cupp (1957). Private Communication in Mouse News Lett. 16, 37.

St. Amand, W. & Cupp, M. B. (1957). Private communication in *Mouse News Lett.* **16,** 37.

Searle, A. G. (1961). Tipsy, a new mutant in linkage group VII of the mouse. *Genet. Res.* **2,** 122–126.

Shreffler, D. C. (1963). Linkage of the mouse transferrin locus. *J. Hered.* **54,** 127–129.

Sokoloff, A. (1964). Sex and crossing over in *Tribolium castaneum*. *Genetics,* **50,** 491–496.

Suomalainen, Esko (1965). On the chromosomes of the geometrid moth genus Cidaria. *Chromosoma* **16,** 166–184.

Wallace, M. E. (1957). A balanced three-point experiment for linkage group V of the house mouse. *Heredity, Lond.* **11,** 223–258.

Warren, D. C. (1940). Crossing over and sex in the fowl. *Am. Nat.* **74,** 93–95.

Yamamoto, T. (1961). Progenies of sex-reversal females mated with sex-reversal males in the Medaka, *Oryzias latipes*. *J. exp. Zool.* **146,** 163–179.

https://doi.org/10.1017/S0016672300010491 Published online by Cambridge University Press