

SPECIAL ARTICLES

DIRECT PROOF THROUGH NON-DISJUNCTION  
THAT THE SEX-LINKED GENES OF *DROSOPHILA*  
ARE BORNE BY THE X-CHROMOSOME

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In "Non-disjunction of the Sex-chromosomes of *Drosophila*," *Jour. Exp. Zool.*, November, 1913, the following case was presented:

1. In certain strains involving sex-linked characters, females arose which could not be explained upon the ordinary mechanism of sex-linked inheritance. These females were maternal in appearance, showing those sex-linked characters which the mother showed, but no influence of those borne by the father.

2. Breeding results showed that genetically as well as somatically these exceptional females were exact duplicates of their mother in that they carried no sex-linked genes introduced by the father.

3. Such exceptionally produced females inherit directly from their mother the power of producing like exceptions; for these females, in turn, gave in  $F_1$ , when outcrossed to any male, five per cent. of daughters like themselves somatically and genetically. The remaining daughters are, in appearance, of the types expected on normal sex-linkage.

4. Exceptionally produced females gave in  $F_1$  a class of sons (five per cent.) complementary to the matroclinous daughters in that these sons both somatically and genetically were purely paternal, having no sex-linked characters introduced by the mother.

5. The entire set of sex-linked genes of the mother, or the entire set of sex-linked genes of the father, appeared without addition or loss in the matroclinous daughters or patroclinous sons, respectively. This result was independent of the particular composition of the mother or father and held when the mother was mated to any male.

6. The exceptional  $F_1$  males (patroclinous) when outcrossed to unrelated females did not give rise to exceptions in  $F_1$ .

7. By breeding in each generation from the exceptional daughters a "pseudo-parthenogenetic" line was maintained in which a given sex-linked constitution was handed down indefinitely from daughter to daughter.

8. The exceptional daughters resulted from the fertilization of an egg of the mother by a normal sperm from the father, as was proved by the introduction into the exceptional daughters of *non*-sex-linked genes from the father. The inheritance was uniparental with respect to sex-linked genes, and biparental and quite regular with respect to non-sex-linked genes.

9. The cytological work of Miss Stevens was referred to as showing that in *Drosophila* the female has two *X*-chromosomes and the male an unpaired *X*. (See, however, section 17.)

The explanation advanced for this series of facts was that *the sex-linked genes were borne by the X-chromosome, and that ten per cent. of the eggs of the exceptional females retained both X-chromosomes or, conversely, lost both to the polar body.*

It was suggested that the cause of the non-disjunction was itself a sex-linked gene.

Work which has been carried out since the previous paper was published enables me to add the following points:

10. Half of the expected class of *daughters* from a non-disjunctive female by *any* male, inherit directly from their mother the same power of producing five per cent. of matroclinous daughters and patroclinous sons. For example, white non-disjunctive females mated to wild males gave in  $F_1$  the following:

Expected classes.	Exceptions.
95% of both sexes.	5% of both sexes.
wild type female	white female
white male	wild type male

Half of the wild-type daughters (all were heterozygous for recessive white) when outcrossed to barred males (barred is a dominant sex-linked character) gave exceptions as follows:

Expected classes.	Exceptions.
95% of both sexes.	5% of both sexes.
Barred female (2)	Wild type female
wild type male (1)	barred male
white male (1)	

11. Non-disjunctional females are diploid in constitution, for (see 10) they can be *heterozygous* in various sex-linked genes, and they then give all the expected classes in the normal proportions.

12. Half of the *expected* class of *sons* (from any non-disjunctional female by any male) *transmit* the power of producing exceptions, although they themselves do not possess that power. Thus, half the white sons of a white non-disjunctional female outcrossed to wild females give in  $F_1$  only the expected classes of wild-type females and wild-type males. If these wild-type daughters are tested by outcrossing to barred males exceptions are found among their offspring.

13. Those sons (half the expected class) which do transmit the power of producing exceptions transmit it *to only some of their daughters and not to all*. Thus of the wild-type daughters tested (in 12) by barred males only approximately half showed exceptions, the others giving only expected classes.

14. The patroclinous sons of a non-disjunctional female do not transmit non-disjunction to any of their offspring.

15. Attempts to localize a gene for non-disjunction in the series of sex-linked genes showed that no such definite locus in the series could be assigned to non-disjunction as has been assigned in the case all sex-linked genes. Non-disjunction was found to assort freely from all sex-linked genes tried.

16. Attempts to obtain pure stock of non-disjunction failed. Had there been an X-chromosome gene involved, the rigorous method used would not have failed to yield a stock pure for that gene.

17. Recent cytological investigation has clearly shown that normally in *Drosophila ampelophila* the female bears two X-chromosomes, and the male an unequal X-Y pair (see 9).

This last fact requires us to substitute the term Y-bearing sperm for "no-X" sperm and Y-egg for no-X egg, in our explanation.

The breeding work (especially 13, 15 and 16) showed that an X-chromosome gene could not be the cause of the phenomenon, and the cytological work (see 17) supplies us with an adequate cause in the supposed presence in the exceptional females of a Y-chromosome in addition to the normal two X-chromosomes.

The prediction was accordingly made that half the daughters of a non-disjunctional female would be found to contain in addition to the two X-chromosomes a supernumerary chromosome which is a Y.

18. *Cytological investigation has shown that approximately one half of the daughters of a non-disjunctional female do in fact*

*contain a supernumerary Y-chromosome, while the remaining half contain only the normal two X-chromosomes.*

The sex-chromosomal constitution of a non-disjunctional female is XXY. In 90 per cent. of the maturations the sex-chromosomes must be placed in opposition to each other in such a way that an X and Y both pass to one pole, and a single X to the other. In ten per cent. of the maturations, however, the chromosomes must oppose each other in such a way that the Y passes to one pole by itself and the two X-chromosomes pass to the other pole together.

The fertilization of these types of eggs by the spermatozoa of an unrelated male of the constitution XY explains the genetical results as follows:

The XX eggs (5 per cent.) by the Y-sperm give females (XX=female) having each a supernumerary Y-chromosome. These females will be exact duplicates of their mother with respect to their chromosomes, *and the breeding work showed that they are exact duplicates with respect to all sex-linked genes* (see 1, 2 and 5). *This parallelism can only be explained by (assuming that the X-chromosomes do in reality bear the genes for the sex-linked characters.*

Furthermore, since these females received no X-chromosome from the father they can neither show nor transmit sex-linked characters from the male (see 1 and 2).

Since the composition of these females is XXY, they will themselves have the power of producing exceptions as did their mother (see 3). The particular composition of the mother can thus be handed on indefinitely from daughter to daughter (see 7).

Only the sex-chromosomes are concerned in this unique maturation and breeding results show that only sex-linked characters are subject to exception in these cases (see 8).

The Y-eggs (5 per cent.) by the X-sperm give males (XY) with no supernumerary chromosomes. These males have received their X-chromosomes from their father and the breeding results (see 4) show that in all sex-linked characters (see 5) they are exact duplicates of the father.

These males will be able neither to produce exceptions (see 6) nor to transmit the power of producing exceptions (see 14) since their chromosome mechanism is that of any ordinary male (see 17).

The XY-eggs (45 per cent.) by the X-sperm will give females (diploid with respect to X (see 11)) which will, to all appearances, be the type expected from the cross, since they will exhibit

characters from either or both parents. But since they contain a supernumerary *Y*-chromosome they will themselves be able to produce exceptions, and breeding tests showed that half the expected females do in fact produce such exceptions (see 10).

19. Such non-disjunctive females which are heterozygous for recessive characters, when bred to any male, produce exceptional daughters which are of one type only, namely, heterozygous dominants. This fact shows that the *non-disjunction occurs at the reduction division*, for if at the reduction division the *X*-chromosomes separated the egg would receive either the dominant bearing chromosome or the recessive bearing chromosome. After the following equational division of the chromosomes two *like* chromosomes would be produced, both dominant or both recessive bearing. If non-disjunction occurred at this stage (2d polar body) exceptional daughters pure dominant or pure recessive would appear. Since females of this type do not appear, we must conclude that the non-disjunction occurs normally at the reduction division and not at the equational division.

The *XY*-eggs (45 per cent.) by *Y*-sperm give males (*XY* = male) with a supernumerary *Y*-chromosome. Since these males receive their *Y*-chromosomes from their mother they will be of the expected classes of sons (see 12). In the spermatogenesis of such males the extra *Y* may go either with *X* or with the other *Y* and these two cases seem to occur with equal frequency. The spermatozoa of such a male are then of four types: *XY-Y-X-YY*. When mated to any female only expected offspring could appear (see 12). The types *XY* and *X* are female producing. Some of the daughters produced will thus have a supernumerary *Y* and will themselves produce exceptions (see 12 and 13).

Some of the sons of such a cross would possess the power of transmitting non-disjunction as did their father of like composition (see 12 and 13). Although the presence of the males having the composition *XYY* has been proven genetically, their occurrence has not yet been studied cytologically.

If in a non-disjunctive female *Y* went equally often with either *X*, then no linkage would be shown between non-disjunction and any sex-linked gene (see 15).

Likewise the method which would unfailingly secure a pure stock of any sex-linked gene is utterly useless for a freely segregating *Y*-chromosome (see 16).

In conclusion, *there can be no doubt that the complete parallelism between the unique behavior of the chromosomes and*

*the behavior of sex-linked genes and sex in this case means that the sex-linked genes are located in and borne by the X-chromosomes.*

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Bridges, C. B. 1914. Direct proof through non-disjunction that the sex-linked genes of *Drosophila* are borne on the X-chromosome, *Science*, N. S. Vol. XL: 107-109.