SURVIVORSHIP PATTERNS IN EARLY ONTOGENY
- IN THE MEDAWAR MODE

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ABSTRACT: Medawar's theory of the evolution of senscence provides the framework for further speculation on the onset times of genetic expressions during the pre-reproductive period. Some of these expressions can be survival enhancing, while some others can place survival at risk; and either of these may be "sustained" (continuing onward from the first appearance in an individual's ontogeny), or "episodic" (lasting for but a short duration). Different adaptive expectations are associated with sustained and episodic effects. Sustained beneficial effects are expected to appear as early as possible in ontogeny, and they have been considered by Gleeson (1984). In many cases, however, selection will not favor the earliest appearance of enhancing <u>episodic</u> events. The predicted distribution of episodic benefits will depend on such factors as iteroparity versus semelparity, the intensity and duration of parental care, and the distribution of inescapable risky episodes (e.g. such as those occuring during embryonic modification). Likewise, the distribution of inescapable risky events themselves, during pre-reproductive ontogeny, will depend on developmental and life-history parameters. Some models are offered and comparisons are made with data from human populations.
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INTRODUCTION

Several years ago Gleeson (1984) provided an appropriate reminder of Medawar's contributions to the evolutionary theory of senescence (e.g. Medawar 1957, 1981), and briefly speculated upon extensions of the theory into early ontogeny. Medawar's approach is based upon two major assumptions. The first is that the time of onset of a genetic expression may, itself, be an inherited trait that varies among individuals in a population. The second assumption is closely allied to the first; it proposes that the timing of the onset of a genetic expression may be controlled by selection. Hence, temporal shifting of a genetic expression, altering its schedule of appearance during an individual's ontogeny, is adaptatively based. Thus, for instance, the onsets of certain deleterious genetic effects can be postponed past the first reproductive period into older ages of individuals. In fact Medawar cites life history data to support his theoretical propositions.

These kinds of approaches are frequently challenged today as "adaptationist," a term emergent from several cautionary papers (especially Gould and Lewontin 1979) that warn of the pitfalls of assessing adaptive bases in biological phenomena. While the warning is necessary, and human investigators can sometimes demonstrate an unconscious ingenuity in adaptively rationalizing biological observations, I disagree that all such approaches should be summarily condemned. Medawar's senescence hypothesis, for example, offers an extremely interesting possiblity. Corroboration of life history information provides a degree of credibility to his view (but no proof of it), showing that this concept of senescence cannot be rejected from consideration.
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The present paper follows some other publications (e.g. Hamilton 1966, Emlen 1970, Frazzetta 1975, Charlesworth 1980, Rose and Charlesworth 1981a, 1981b, Rose 1982, Gleeson 1984, and Rose and Service 1985) that investigate adaptive aspects of Medawar's model. The main focus here is to differentiate between sustained and episodic events, an important distinction that has not received careful attention previously. These arguments will be framed within the context of Medawar's approach, and hence will consider possible adaptive implications.

BACKGROUND: The Medawar model assumes the existence of genetic effects that possess both beneficial and deleterious consequences. (Were it not for this duality, a gene with a simple deleterious expression would be selectively disfavored, and eventually removed). In these cases of "antagonistic pleiotropy" (Rose 1982) any tendency to postpone the harmful effects beyond an individual's reproductive age will be advantageous. And, a tendency to draw beneficial expressions toward an early age (retrieving them, perhaps, from older age), will be favorable. It is, however, also important to note that early onsets of beneficial traits may arise from incorporation of genes having no deleterious pleiotropic effects (Emlen 1970, Rose and Service 1985).

Medawar produced a most pointed demonstration (1957) in a hypothetical population in which individuals do not undergo a senescent decline with age. Even here, where the older population constituents have no greater prospect of death than those younger, the cumulative effects of random fatal occurrences will increasingly reduce the expectation (calculated at an individual's birth) of survivorship into advancing years. Hence, there is a decided advantage in scheduling the appearance of beneficial traits toward an earlier period in life. And deleterious traits delayed long enough in ontogeny will do relatively little harm. The evolutionary result is senescence, in both survival and (direct) reproductive capacities.

This view is basically supported by Rose and Charlesworth (1981a, 1981b). There is, in fact, considerable agreement among authors who publish within the context of the Medawar model, and who concentrate on the ontogenetic period from first reproduction onward. The pre-reproductive period, however, is either relatively ignored, or when not, is the focus of greater controversy.

ONSETS OF EXPRESSIONS IN EARLY ONTOGENY

Beneficial Traits.

Let us consider an assumption: that the age of first reproduction is the target age of onset of beneficial traits. Taking this approach, the incorporation rate of mutations having this onset schedule should tend to be greatest. Also, advantageous features originally appearing later than first reproductive age would be drawn toward it; but those initially arising before reproduction would be delayed to approach the reproductive period. This notion has been reviewed by Gleeson (1984) who, instead, proposes that sustained beneficial effects should undergo precession all the way back to conception. Precession back to the zygote is, indeed, expected for sustained advantageous traits, but not necessarily for traits that do not last.

It is conceivable that there is a class of beneficial traits that are not sustained, but instead are episodic in that their effects are transitory, vanishing sometime after onset long before the individual has attained very old age. Gleeson is careful not to confuse the two kinds of effects, but does not dwell upon those that are episodic. While the demarcation between the two may in some cases be faint, as where the "episode" is very long enduring, a dichotomy is appropriate because their evolutionary implications differ.

Sustained advantages confer benefits from their onset and throughout all subsequent ages. Hence, early expression strengthens the chances of survival of the individual throughout its remaining life. Episodic benefits arise and then depart, providing the individual a short-term boost of strength followed by relative

weakness. Whether or not episodic onsets of benefits would tend to shift toward conception will not be straightforward, but will depend upon several factors. One of these will relate to obligate periods of inherent risk during development. Another will be influenced by the duration and quality of parental care, and other factors involving the parents.

Development of complex organisms is a near continuum of modification, involving a succession of periods when both chemical and morphological entities are changing and interacting, and intricately producing epigenetic ramifications having potentially broad influences. Embryonic transformations, and metamorphic transitions in animals having larval phases, are drastic and risky as has been demonstrated, for example, by Anderson et al (1971). If we assume that selection cannot remove these inherent risks, we might hypothesize that episodic strengths might be shifted to cover them, thus diluting their potentially dangerous effects. If there were no limitations on early ontogenetic shifting, the distribution of these beneficial episodes would then match that of the most harmful periods obligated by developmental processes.

The issue of parental care is easiest to consider in isolation from other intruding factors, such as those of developmental risks just noted. Clearly, in reality, parental and developmental factors (and any relevant others) will interplay in complicated ways. Even by itself, however, parental care will theoretically influence the scheduling of episodic benefits.

Parental care varies from the minimum of a female carrying unfertilized eggs to be released, united with sperm externally, and forgotten, to the maximum of extended postnatal doting as in humans. From a biological viewpoint, the worst thing that can happen to a parent is to invest energy (and risk one's own survival) in offspring who do not reproduce. (Reproductive failure of the offspring can be the result of deficits in either or both fertility and survivorship, but in this paper I consider survivorship traits alone.) The amount of energetic investment and risk given and suffered by a parent of any species is related to the duration of parental care. Hamilton (1966; amplified in Emlen 1970 and in Frazzetta 1975) has argued that inherently weak offspring, having little chance of making it to reproductive age, favor the parents by dying early in the parental-care period, thus restoring to the parents an increased survivorship and improved chances for more successful reproduction later.

The implication of Hamilton's conclusion is that episodic benefits will probably not undergo precession toward conception. On such theoretical grounds, these advantageous effects will most likely become more densely congregated toward the latter part of the period of parental investment. They should reach their greatest combined strength as parental care ends, and maintain this high level through the age of first reproduction.

Deleterious Traits.

Both "deleterious" and "beneficial" in the context of this paper are terms having a slight ambiguity. They could be seen as representing absolute harm or advantage, while in fact a more general view might consider them as relative to one another. Hence, a deleterious feature might be assessable only in comparison to one of greater benefit. Also, there are certain instances where relative harm and benefit of a single ontogenetic event are not easily separated. For example, the process of gastrulation in vertebrate development is essential in producing a complex organism, but it also initiates a rapid cascade of critical effects that place the survival of the embryo at increased risk. Hence, this period spells the onset of a "deleterious" trait, but without which things would be far worse for the individual in its near future.

Such pre-reproductive episodes of risk, tied to developmental events, are obligatory and not readily reducible through evolution under natural selection. They, in a sense, fall into a broadened definition of Rose's (1982) category of

antagonistic pleiotropy (see above). In most circumstances then, at best, the onset schedules of these risky episodes might be but slightly shifted.

On purely theoretical grounds, should it make a difference how these events are scheduled? And if so, what distribution is expected? Apparently Charlesworth (1980) assumes that there should be no relative advantage of one schedule over another during early ontogeny for he suggests that "there should be no selection for changes in distribution of mortality during the pre-reproductive period." However, I propose that there are two kinds of factors through this period that might well fall under discerning selection. The first of these relates to the survival of the young offspring, and the second to the survival and future reproductive prospects of the parents. Advantageous scheduling to accomodate either one of these groups is not necessarily compatible with accomodation of the other, and in some small sense there is a "competition" between parents and offspring. Theoretically, the equilibrium outcome established by selection through successive generations will be a compromise.

In reality, there may be little or no significant chance of shifting the onset of certain developmental events, and because many such episodes are sequelae to others, the schedulings within the whole developmental program may be somewhat inertial to change. Where changes, including temporal separations of some events in early ontogeny, are actually possible, it seems unlikely that a number of different risks will be piled up together at the same onset age. The simultaneity of diverse risks could theoretically overwhelm the young offspring. Hence, the expectation is a temporal separation of the riskiest episodes when possible. The best insurance for an offspring's survival, when many risky episodes can be shifted to best advantage, is an approximately even temporal spacing between the obligate risks.

The theoretically best arrangement of these episodes, from the offspring's standpoint, will not quite coincide with the optimum parental advantage. From the parent's point of view, it is far better to lose an offspring earlier than later in its pre-reproductive period, and inherently weak progeny - whose prospects of survival through reproductive age are decidedly dim - should be "tested" and perhaps lost at the very start of the period of parental expenditure. Thus it would be expected that the risky episodes through this time would not be equally spaced, but instead be concentrated toward the beginning of the parental care period. The compromise between separation and concentration would produce a distribution of risky episodes that was basically a reversed logarithmic spacing (fig. 1).

Harmful episodes are cleared away from the ontogenetic span between the end of intense parental involvement and first reproductive age. Risky events, originally expressed at the start of that span, would tend to be shifted into earlier age; but those toward the span's termination would be postponed as long as possible (thus contributing to senescent decline in late life).

Factors Of Parental Care.

In the proposed model the theoretically expected outcomes will depend upon the intensity and quality of parental care provided. A female frog expends energy in producing and carrying a burden of unfertilized eggs, and the care involved ends when the eggs are released. This care is minimal, and the unfruitful impediment of one "inferior" egg that either will not completely mature, or once fertilized, will probably not result in a reproductive offspring, is seemingly minor. However, a large proportion of such inferior eggs could add significant risk to female survival without compensating prospects of future reproductive repayment. Thus it is possible that today's average gravid frog and her contained mass of eggs is the product of generations of a selective regimen, and hence, that the burden of hopeless eggs has been diminished.

Most clearly, however, it is easiest to envision the present theoretical model's implications in cases of extended and intense parental care. Mammals and birds are examples of such parental investment, and are also germane in that the vast majority (at least) of their constituent species are iteroparous. It is obvious that strictly

semelparous species - those that attempt reproduction just once, whether or not that first effort succeeds - lie well outside of the model's accomodation; early offspring mortality in such cases adds nothing to parental prospects of further reproduction. It is, perhaps, worth noting that in semelparous species the expected distribution of deleterious episodes in the pre-reproductive period would not be spaced in the pattern suggested for iteroparous forms, but would be separated more evenly - or perhaps more erratically (either spacing pattern in contrast to that shown in fig. 1).
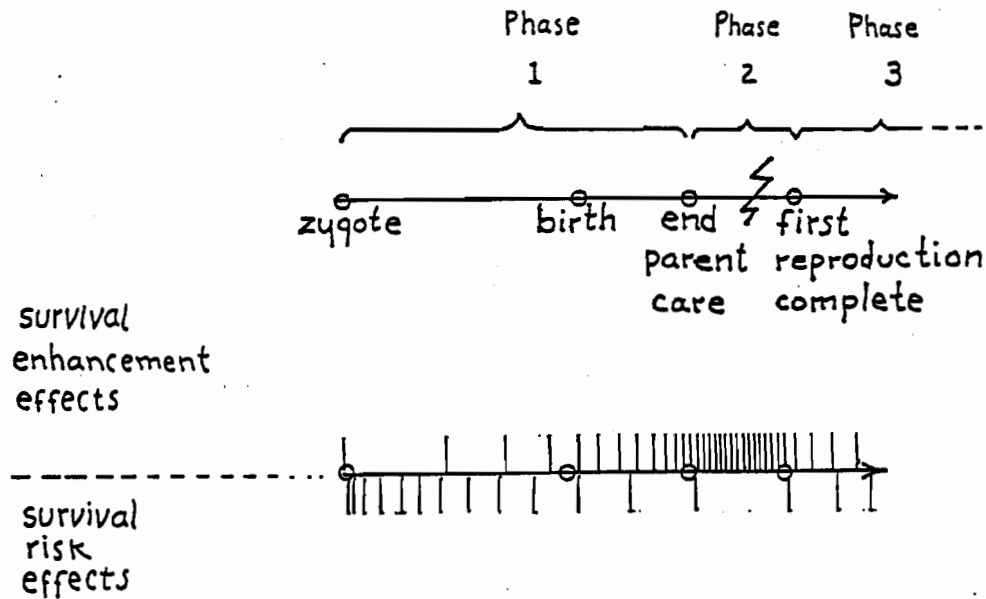

Figure 1. Hypothetical temporal arrangement of episodic survival-enhancement effects, and episodic survival-risk effects, appearing in an average individual's ontogeny. It is assumed that the individual's species is iteroparous, that there is significant postnatal parental care, and that each episode duration is "short" (e.g. one-tenth or less the duration of the embryonic period). The model is intended to consider intrinsic characteristics only; hence (and see text and fig. 2), non-genetic effects of parental protection are not accomodated, and thus the "end of parental care" refers to the termination of obligatory care as, hypothetically, an evolutionary factor in foundational populations. In Phase 1 the risks are logarithmically spaced, while the enhancements have a reversed log distribution. In Phase 2 the spacing for both beneficial and detrimental episodes is an even distribution; ideally, risks would be few in this phase, and enhancements numerous. Later, in Phase 3 enhancements decrease, while risk episodes enlarge. In contrast to this model, a strictly semelparous species would show no regular distributional changes through the first two phases, and both risks and enhancements would be evenly (or, perhaps erratically) spaced. Note: the slash between end of parental care and the completion of reproduction indicates that the length of this period will probably be longer than indicated by the horizontal line length.

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        There are conceivable cases where an iteroparous species may be functionally almost semelparous, and deserve note. A colonizing species may produce a great many offspring in any one reproductive period, each with little chance of survival.

Likewise, the parents themselves may only rarely survive to a second reproductive season and, while technically they may be iteroparous, are virtually limited to a single breeding.

A related case of (approximate) semelparity in iteroparous species may occur when the population is growing very rapidly. In such instances the instrinsic rate of population increase (r) has a high value, and the reproductive value (v_x/v_o; see Fisher 1930) of an average individual reaches a peak near first reproductive age, but drops precipitously thereafter. The cause of this marked decline is due to the difference in proportionate contributions of early versus late offspring (Frazzetta 1975). In a rapidly growing population an individual's later offspring are a smaller fraction of all offspring being produced at that time by all the population's parents together. Hence, if r is extremely large, early progeny from an individual are so much more significant than later ones that the later ones are discountable - or nearly so - as a contribution. However, such extreme cases are probably rare in mammals and birds, and temporary if and when they do occur. Moreover, these views do not account for second or later progeny having a higher survival rate than the first, as the parents gain experience in the raising of their young.

Humans are an iteroparous species (in recent history, too much so), and are evolved to lavish long, intense care on their direct offspring. Infants and very young children are clearly not self-supporting, and this fact makes the definition of "first reproductive age" for humans (and some other species) a little muddy. A human female has not, biologically, completed a reproduction at the mere birth of an offspring. The completion comes later, in degrees, only beginning at the age when the progeny has at least some chance of self-sufficiency. Hence, the biologically realistic age of initial reproduction of a human female most probably should be defined as the sum of her earliest parturition age plus the first six to ten years following the birth of her primary offspring. This suggests a "first reproduction age" at a little past 20 years old. And from an offspring's side of the matter, the end to essential parental care will materialize at around the first decade of life.

Discussion

The model proposed above has some corroborative support from human mortality curves, particularly the age-specific mortality (μ_x) which is the probability of death within the interval beginning at age x and concluding at $x+1$. Emlen (1970) called attention to this source of evidence as fitting the results of his mathematical argument, and also appropriately he hinted that some details of the mortality curves wander away from pure theoretical prediction. Figure 2 shows several curves modified (redrawn on linear coordinates from semi-log plots) from Upton (1977). It is clear that geographic - perhaps cultural - differences are revealed in such parameters as the minimum value of μ_x, rate of increase of mortality following parental care, and the age where a significant rise in post-parental-care mortality begins. Upton's comparison of human statistics from Sweden, from data of the middle 18th to those of the 20th Century, suggest that even within the same geographic region such differences can exist; these may result from changes in cultural conventions, political structure and events, advances in health care, and possibly additional factors.

Despite these differences, similarities are also evident. The lowest age-specific mortality occurs at around ten years old. From that point, mortality tends to increase slightly at first, then gradually gains in rate toward about 50 or 60 years, whereupon it increases drastically. Mild fluctuations seem common in the period between about ten and 50 years of age.

The high mortality of young children fit with the model presented here, as does the reduction of mortality to its lowest point at the age when essential parental care is ending. The relatively low level of mortality following the cessation of care through first reproduction, and the marked increase in death risk much later are also consistent with this model (and aspects of other authors' models).
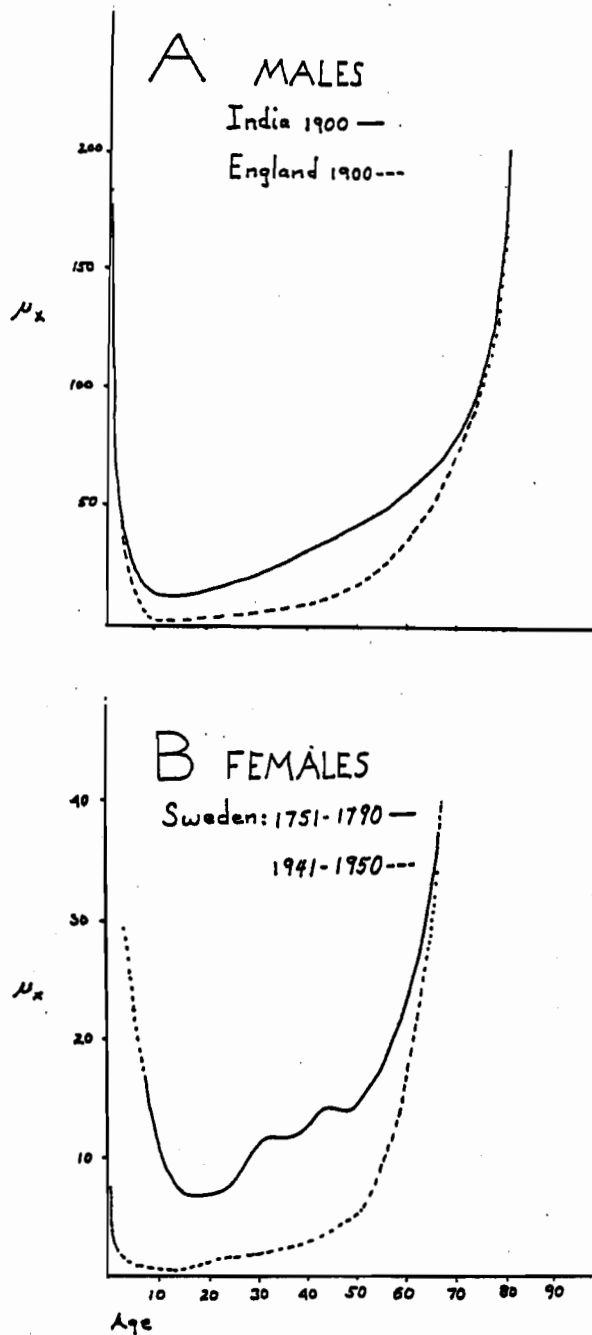
Figure 2.   Age-specific mortality (μ_x) in human populations. A.   Males compared
between India and England in 1900. B. Females in Sweden compared between data from
two centuries. Data redrawn from Upton (1977).

However, in the purest prediction from the present model, the lowest point of
mortality at the end of essential parental care should be continued as a horizontal
line on the μ_x curve until the first reproduction is realistically completed. Only
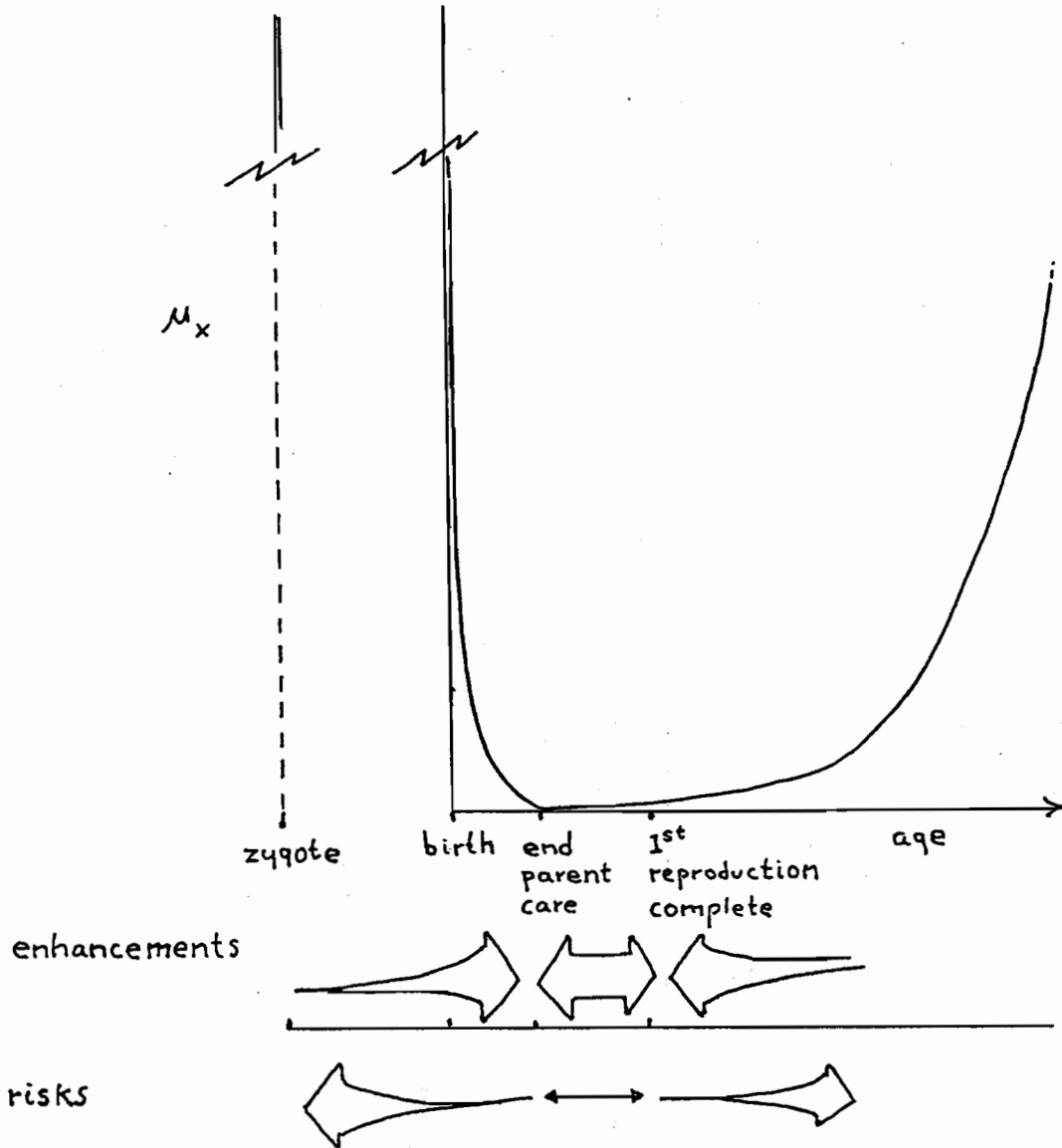
Figure 3. Hypothesized strengths of precessive (arrows pointing left) or recessive (arrows pointing right) rescheduling of genetic expression, or of probabilities of gene incorporation through selection having enhancing or risky effects at indicated ontogenetic times. The upper drawing is a human μ_x curve (see fig. 2), and is shown (by the dashed ordinate axis to the left) as including consideration of prenatal events backward to the zygote. Prenatal mortality is estimated as extremely higher than that following birth, and the slashes on the ordinates indicate disjunctiures to represent the inequality in heights of plotted ordinate points between pre- and postnatal periods. The lower drawing shows the strengths of rescheduling (through precession or recession), or of probabilities of gene incorporation, based upon hypothesized differences in intensity of natural selection between real or theoretical alternatives of onset schedules. The strength or probability in each ontogenetic region is proportional to the thickness of the arrow in that location. Iteroparity is assumed.

after the initial reproduction should it rise, and then only slightly to secure additional, early, reproductive periods within nearly the same prospects of parental viability. Instead we see that the line rises from its lowest mark at the end of the span of parental care, inclining upward toward the first reproductive age. Indeed, in many of the mortality curves presented by Upton (1977), the slopes of the curves tend to rise immediately following the termination of essential care, and then flatten to a lesser, but still positive slope (but to rise sharply later).

Many factors, both imaginable and unimaginable, could underlie this apparent deviation of curve shape away from that of the model's expectation. For example, the overall increase in mortality from the end of parental care to first reproduction could be explained as the result of two possible causes. The first is that at the termination of parental care, the offspring becomes independent of parental protection to augment its own self-protection; hence, mortality rises. The second is that preparation for the first reproduction, with its attendant ontogenetic physiological changes and behavioral modifications, is probably not related to survival, and viability aspects of life are compromised in this period.

While these two last explanations are possibly reasonable, we must separate intrinsic traits that could have been evolved in early, foundational human populations, from those caused by more proximate factors. For example, mortality curves compared over centuries in Sweden show a nearly identical pattern in that the lowest mortality occurs at close to ten years old, and rises immediately from thereon, although the slope of this rise differs between earliest and most recent populations (fig. 2B). The occurrence of minimum μ_x at around age ten might have evolved in foundational populations and become incorporated as an intrinsic trait. The rate of rise in mortality from that lowest point differs through historic periods, and in two centuries it would seem that parental-care protocols might change significantly. Humans alter their definitions of a "child," even within relatively short historic periods, often to result in modified parental-care modes that change the temporal limits of protection. An average offspring in one historic interval might be favored with a longer term of parental care (hence prospect of viability) than a child at another time. Thus, the slope of increased mortality following age ten may differ accordingly.

There is a great lack of information concerning age-related mortality of embryos, and I know of no tables or other data that statistically relate fetal risk to developmental events (except in offspring free of parental concern, as in Anderson et al 1971). While embryonic mortality is a central issue in this paper, crucial information is lacking.

Age-specific mortality in human populations (fig. 2) does not begin to rise drastically until near 50 years of age. In humans an individual can contribute significantly to his or her own second generation of offspring, and thus it appears that there has been selection to preserve life beyond the birth of one's grandchildren.

The final illustration (fig. 3) models the views of this paper within the context of precession and recession, but can also be read from another standpoint: the relative probabilities (or rates; Emlen 1970) of selectively incorporating different, new mutations already each equipped with its onset characteristics (see earlier). In the context of precessional and recessional shifts, this figure assumes that alterations in scheduling are gradual, not saltational relative to ontogenetic age. The figure suggests that a mortality schedule has already evolved (as shown by the upper curve), and that a new mutant gene, which either incorporates novel phenotypic effects, or reschedules old ones, is being "assessed" by selection.

Available information concerning post-natal survival suggests possible agreement with those views presented here, and with other related interpretations offered by other authors. Even though a number of questions remain unsatisfied, the potentiality of an evolutionary role in the ontogenetic scheduling of strengths and risks cannot be dismissed. It is thus proper that all future research on aging and

other life-history phenomena, however slated, take care not to neglect evolutionary factors from analytic considerations. This is the lesson from Medawar.

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