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Problems in comparisons of data for the prevalence of myopia and the frequency distribution of ametropia

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Abstract

Purpose: There is currently great interest in comparing data for the prevalence of myopia in different parts of the world, particularly in view of the suggestion that, in recent decades, marked increases have occurred in prevalence among children and young adults in some areas. This work investigates the factors that affect the comparison and interpretation of sets of myopia prevalence data for different age groups, locations and dates.

Recent findings: Using data from the literature, the problems caused by the effect of the reliability and validity of the method used to measure refraction, the threshold chosen to define an eye as myopic are discussed. The influence of slow drifts in refraction with age is considered and it is recommended that if mean refractions at different ages are to be compared, the interpretation of the results should take account of the normal age-dependent trends in refraction. The value of specifying the distribution of refractive errors, rather than simply their mean and standard deviation, is emphasised and possible parametric fits to describe these distributions are reviewed.

Summary: There remains a need for greater standardisation in sampling strategies, refractive measurement procedures and definition of myopia in prevalence studies. The use of an ex-Gaussian or other approximations to describe the refractive error distribution appears to give useful insights into the nature of the changes that may occur with age and other factors.

Introduction

It is widely suggested that marked increases in the prevalence of myopia among children and young adults have occurred in recent decades, particularly in the Far East.[1–6] Although the refractive changes underlying this increased prevalence have been followed longitudinally for several years in substantial groups of subjects, as yet there are no data on individual changes over a lifetime, so that discussions of age differences must still largely rely on cross-sectional studies. In particular, such cross-sectional studies are often used to compare the prevalence of myopia in younger and older age groups, on the assumption that the apparently higher prevalences in today's younger generation reflect new environmental factors which were not present during the childhood of today's older populations. *Figure 1* shows an early example of such a comparison.[7] Mean refractions were more myopic and myopia prevalence was much higher in young adults as compared with older members of the Inuit community involved: myopia was taken as a refraction ≤ -0.25 D. The authors therefore argued that new environmental factors were affecting the refraction of the younger generation. Numerous studies have since been undertaken at many different locations and dates in attempts to clarify the extent to which the prevalence of myopia might be changing, and to identify the possible ethnic, environmental or other factors which might be responsible for any such changes. It is obviously desirable that it should be possible to directly compare the data produced by these various studies.

Sorsby[8] criticised several aspects of the work of Young *et al.*[7], pointing out in particular that the large, unusual increase in mean myopia in the 20–25 group might suggest that the volunteer subjects were self-selected on the basis of

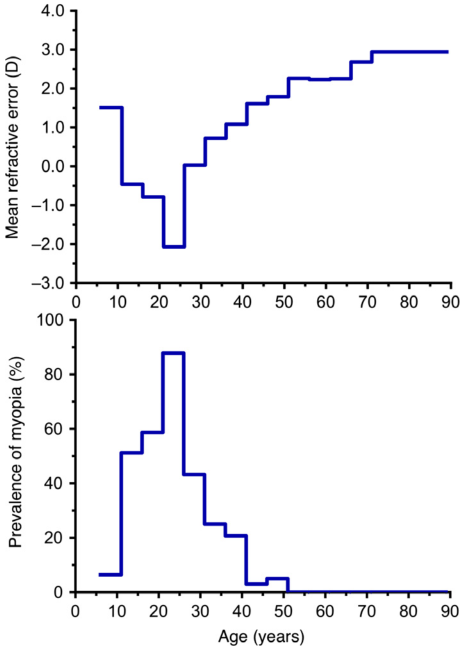

Figure 1. (Top) Cross-sectional data for the mean right eye mean spherical equivalent (MSE) refractive errors for different Inuit age groups at Barrow Point, Alaska. (Bottom) The percentage of myopic eyes in each age group (after Young *et al.* 1969)[7]. Myopia is defined as a refractive error ≤−0.25 D. The study involved the right eyes of 508 individual volunteers.

known visual problems. Although Young[9] mounted a vigorous defence against Sorsby's criticisms, several other authors[10–13] have since suggested that at least some of the evidence for very marked changes in the prevalence of myopia obtained in the many different studies may be weaker than many have suggested. For example, they note that problems in interpreting apparent differences in prevalence might arise:

(1). In comparisons of studies at a single location but at different points in time, or results from different locations. Any refractive differences might be caused, at least in part, by such factors as variations in methodology used (e.g. the refractive technique, use of cycloplegia, testing distance, use of refractions at the spectacle plane, i.e. spectacle refractions, rather than the refractions at the corneal plane, i.e. the ocular refractions), the nature of the population sampled (e.g. ethnicity, parental background, sex ratio) or the criterion used to define "myopia".

(2). In cross-sectional studies at a fixed point in time at a single location, as illustrated in *Figure 1*. Refractive changes with age might reflect normal physiological changes in the eye, rather than changes in such factors as lifestyle, the environment or nutrition.[11] Again there might be differences in the composition of the sample in each age group, for example in its sex ratio or ethnicity.

Some aspects of this more cautious approach to the comparison of different sets of myopia prevalence or other related data are considered further here. It should be emphasised, however, that we are not denying the existence of an increase in the prevalence of myopia in some parts of the world, since this is supported by several studies in which a standardised methodology has been used to track refraction over time in groups of similar age, ethnicity and sex ratio at a single site[14], although more recent data suggest that in some Asian locations prevalence has remained stable, though high, over the last two decades.[15]

We argue first that the distribution of refractive errors is likely to be such that care must be exercised in inferring too much from simple measures of prevalence and mean refractive error, particularly when the threshold criterion used for defining myopia is set at a low value, and that, as recently emphasised by Flitcroft[16,17], the distribution of errors is of much greater significance for the understanding of the nature of any refractive changes that might be occurring. Further, when comparing effects in different age groups, allowance must be made for any gradual refractive changes, which may be an intrinsic part of the ageing process.[11] Finally, we consider how frequency distributions for refractive error might be compared and suggest a useful novel approximation for the distributions that are commonly observed.

Measurements of the distribution of refractive errors and the criterion used to define "myopia"

To illustrate the basic problems under consideration, we take the cycloplegic refractive distribution found by Sorsby *et al.*,[18] for a single eye of each of 1033 unselected young, male, military recruits from the United Kingdom (mostly aged 19–21 inclusive, total range 17–27). The full curve of *Figure 2* gives the distribution of mean spherical equivalent ocular refractions found, and the dashed curve the cumulative distribution. The data in *Figure 2* are quantised in 1 D intervals (0 to +0.9, −0.1 to −1.0, −1.1 to −2.0 D etc). As is well known, this and similar refractive error data for the period,[19,20] are not normally distributed but show a leptokurtic distribution, with most subjects being low hyperopes. Sorsby *et al.'s* data show little skewness but many measured distributions are strongly skewed in the negative direction.

Factors affecting the observed distribution

We note first that any measured distribution of this type represents the true distribution of errors modified by (convolved with) the measurement uncertainties of the

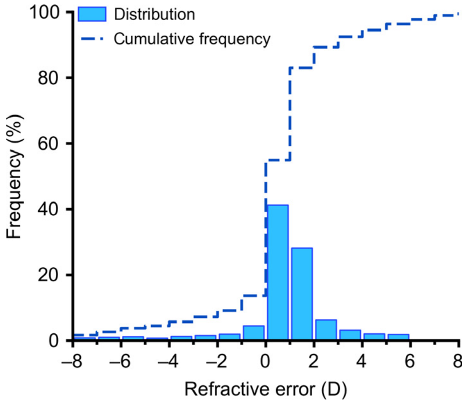

Figure 2. The distribution of mean equivalent spherical refractive errors found by Sorsby *et al.* (1960)[18] (filled bars) and the corresponding cumulative distribution (dashed curve).

refractive technique employed. Most studies of the reliability of refractive methods conclude that the standard deviation of repeated measurements is around 0.30 D[21–23] so that the measured distribution, particularly any central peak, is slightly broadened by the limited reliability of the refractive results. To take an extreme, if highly improbable case, if all eyes were truly emmetropic and measurement errors were normally distributed with a standard deviation of 0.3 D, the apparent prevalence of myopia at the level ≤−0.25 D would be about 20%. Although these effects are less striking with real refractive distributions similar to those of *Figure 2*, where pooling into 1 D frequency bins itself distorts the distribution, their result is that some of the large proportion of true emmetropes and low hyperopes may be measured as low myopes in the range −0.25 to −0.50 D inclusive.

A further consequence of the marked central peak of most refractive distributions and the steep gradient of the cumulative distribution near emmetropia (*Figure 2*) is that the proportion of low myopes may be markedly influenced by details of the refractive technique used. This is particularly the case when younger subjects are refracted with or without cycloplegia, since any accommodation will move the peak in the myopic direction. Systematic differences may also arise from other causes, such as the use of different objective or subjective techniques and endpoints, or different testing distances.

The form of the distribution may also alter with the way in which the "refractive error" is defined. While it is usual to use the mean spherical equivalent (MSE, i.e. sphere + 0.5 * cyl) to specify the error, this is not always the case. It appears that the data of most authors are now usually presented in terms of spectacle refractions, rather than ocular refractions, but this, like the vertex distance at which the measurements were made, is not always clearly stated. Although this has negligible effect upon low values of error, higher negative errors are decreased when spectacle corrections are converted to ocular refractions, while positive errors are increased. (e.g. with a 10 mm vertex distance, an ocular refraction of −5.00 D would become a spectacle refraction of −5.26 D, and +5.00 D would become +4.76 D). Stenstrom[20] noted that use of ocular refractions reduced the skewness of his data. Sorsby *et al.*[18] used ocular, rather than spectacle, refractions and noted, somewhat challengingly, *"the marked degrees of myopia in previous studies are to some extent illusory, as the ocular refraction is much less than the spectacle refraction in these high myopes"*. On the other hand, it could reasonably be argued that spectacle refractions are of greater practical interest.

Prevalence values

It is evident from the cumulative distribution (*Figure 2*) that any figure for the prevalence of myopia will depend upon the criterion used to define "myopia" and that estimated prevalence rises as the magnitude of the chosen negative threshold refractive error decreases.[12,13,24] *Figure 3* reproduces some cumulative distributions for United States children of different ethnicities but similar age (5–17 years).[24] It can be seen that both the absolute and relative prevalences for the different groups will depend upon the cut-off value chosen to define "myopia", with the prevalences falling as the cut-off criterion is made more negative. The impact on prevalence value of any change in threshold obviously depends upon the local gradient of the cumulative frequency distribution.

In practice, in spite of many pleas for standardisation,[12,25–27] there is still no agreement on what the value of the cut-off point should be. Some examples of the values used in studies over the last 50 years are shown in *Table 1*, which also indicates the diversity of several other important

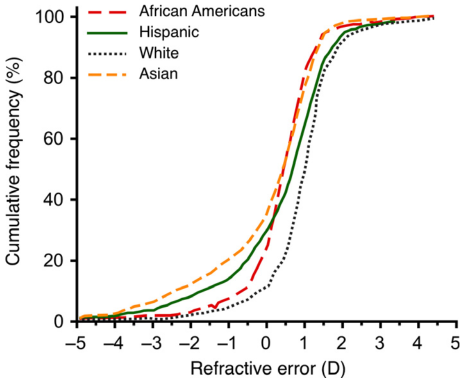

Figure 3. Cumulative frequency of mean spherical error for different ethnic groups aged 5–17 years in the USA (redrawn from Kleinstein *et al.*[24]).

Table 1. Some examples of measurement conditions and threshold criteria used in different studies of myopia prevalence

Study	Method	Cycloplegia	MSE used	Myopia threshold
Sorsby *et al.* (1960)[18]	Ret + Subj	Yes	Mainly	≤−0.10 D
Young *et al.* (1969)[7]	Subj	Yes	Yes	≤−0.25 D
Framingham Offspring Study Group (1996)[28]	Auto	No	Yes	≤−1.00 D
Katz *et al.* (1997)[29]	Subj	No	Yes	<−0.50 D
Lin *et al.* (1996)[30]	Autorefrator + Ret	Yes	Yes	≤−0.25 D
Lin *et al.* (1999)[2]	Auto	Yes	?	<−0.25 D
Kinge & Midelfart (1999)[31]	Auto + Subj	Yes	Yes	≤−0.25 D
Lithander (1999)[32]	Auto + Ret	Yes	Yes	≤−1.00 D
Montes-Mico & Ferre-Blasco (2000)[33]	Ret + Subj	No	Yes	<−0.25 D
Loman *et al.* (2002)[34]	Auto	No	Yes	≤−0.50 D
Kleinstein *et al.* (2003)[24]	Auto	Yes	No	≤−0.75 D[a]
Quek *et al.* (2004)[35]	Auto	No	Yes	≤−0.50 D
Eye Diseases Study Group (2004)[36]	Auto + Subj	No	Yes	≤−1.00 D
Onal *et al.* (2007)[37]	Auto + Subj	Yes	Yes	≤−0.75 D
Vitale *et al.* (2009)[6]	Obj, existing spectacles	No	Yes	<0.00 D
Lam *et al.* (2012)[15]	Auto	No	Yes	<−0.50 D
French *et al.* (2012)[38]	Auto	Yes	Yes	≤−0.50 D
Pan *et al.* (2013)[4]	Auto + Subj	No	Yes	<−0.50 D
Lv & Zhang (2013)[39]	Auto + Subj	Yes	Yes	<−0.50 D
Pan *et al.* (2015)[40]	Auto or Subj	No	Yes	<−0.50 D

Subj, subjective; Obj, objective; Auto, autoefraction; Ret, retinoscopy; MSE, Mean spherical equivalent.
[a]In each principal meridian.

measurement conditions. There appears to be a tendency for more recent investigators to converge towards a threshold value of MSE < -0.50 D. We suggest that a slightly higher value, MSE ≤ -0.75 D, might be a reasonable compromise, since at this level myopia has a marked effect on e.g. visual acuity, which is reduced to around 6/12. This is close to the limits required to meet typical standards of vision for driving,[41,42] and a correction would be recommended by practitioners.

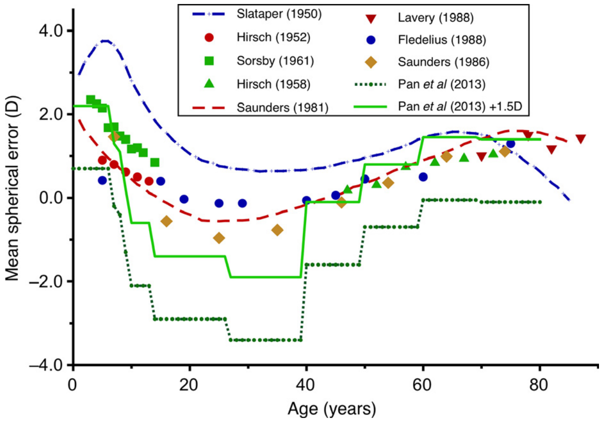

Figure 4. A selection of Western Caucasian data for the changes in mean equivalent spherical refractive error with age in Western populations.[43–50] The green curves show multi-ethnic Singapore data from Pan *et al.*[4] in its original form (dotted, dark green) and shifted upwards by 1.5 D (continuous, pale green).

Age-dependent refractive changes

The further important issue affecting interpretation of changes in prevalence is the question of normal changes in refraction with age.[11] It is known that there are age-dependent changes in several of the biometric parameters affecting the MSE of the eye, particularly the lens. Numerous European and North American authors have compared overall mean refractions at different ages, usually in cross-sectional studies but occasionally longitudinally[43–50] (*Figure 4*). While, as might be expected from the differences in the patient selection criteria and refractive methods employed in the different studies, the results do not agree exactly, they show broad agreement regarding the general nature of the trends involved. Overall mean MSE becomes more myopic until the age of about 30, when it reaches about −0.50 D. It then drifts back in the direction of hyperopia to reach around +1.50 D at about 70 years i.e. a change of about +2.00 D. Thereafter the individual results seem to be strongly influenced by the effects of any pathology, such as cataract. Note that the studies span many decades and that the age trends appear to remain consistent over this period.

What causes these changes in overall mean refraction? The hyperopic shift in later life could either be due to a hyperopic shift in the whole population, so that while the mean became more hyperopic the shape of the distribution of errors was unchanged, or to a larger hyperopic shift in those eyes which were originally more myopic, with changes being smaller or absent in eyes which started emmetropic or hyperopic, thus narrowing the error distribution. In the former case the standard deviation would be unchanged; in the latter it would be reduced. Where available, the data suggest that after the age of 30 the shape of the distribution as indicated by its standard deviation or percentiles does not change greatly,[43,48] so that age-related ocular changes common to all eyes, such as those in the crystalline lens,[11] may be largely responsible for the hyperopic trend.

The hyperopic trend in later adult life implies that caution must be exercised before it is claimed that novel environmental conditions have caused higher levels of myopia in the younger age group (e.g. *Figure 1*). It is also of interest that the slow drift with age means that the distribution of adult refractive errors will be broadened when the subject group contains individuals covering a wider range of ages than those in e.g. the studies by Stromberg[19] or Sorsby *et al.*[18] Mutti & Zadnik[11] consider the question of natural physiological change from a slightly different viewpoint, the prevalence of myopia at different ages, but their basic argument is essentially similar to that offered here.

In fact, insofar as it is valid to compare data for Asian eyes with the progression data obtained in Europe and North America, there is strong evidence that Asian data are different. The dark-green dotted curve in *Figure 4* shows a synthesis by Pan *et al.*[4] of various data from recent studies in Singapore. While the general shape is similar to the earlier Western data, the refractions are generally more myopic at all ages. If the curve is translated upwards by +1.50 D to obtain rough agreement with western data in the youngest age groups (continuous, pale-green curve), young adults are still more myopic, although the older adults come into agreement with the earlier data. This implies that genetically the infant Asian eye may be more myopic and that the rate at which myopia develops through childhood and adolescence is faster than was historically the case in the West. The cross-sectional changes in later life can be interpreted as either supporting the view that older generations developed less myopia or that there has always been a more rapid drift in the hyperopic direction in older Chinese eyes (see below).

It is also of interest that it is not possible to explain the age changes in the cross-sectional data of Young *et al.*[7] for Inuits (*Figure 1*) simply in terms of changes comparable to those for Caucasian eyes as illustrated in *Figure 4*. *Figure 5* gives a comparison of the Young *et al.'s* refractive data with mean data from the cross-sectional[43] and longitudinal[45] Caucasian studies of Saunders. The changes are markedly larger in the Inuits, mainly because the older eyes are more hypermetropic. Also shown in *Figure 5* is a smoothed curvilinear fit to cross-sectional data for a similar group of 133 Alaskan Inuits obtained some 30 years later by Wojciechowski *et al.*[51]: the curve appears to be shifted along the age axis with respect to the earlier data of Young and his colleagues by about the amount that might be expected on the basis of the dates of the two studies and a cohort effect. Unfortunately the later study did not include ages younger than 40 years.

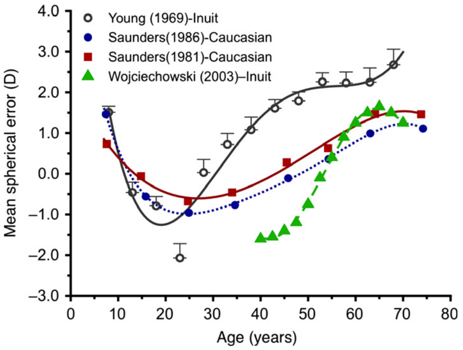

Figure 5. Comparison of the changes in mean refractive error with age from the data of Young *et al.* (1969)[7] for Inuits and Caucasian data from Saunders (1981, cross-sectional data[43]; 1986 longitudinal data[45]). The error bars for the Young data correspond to +1 standard errors. The continuous and dotted curves are 5th-order polynomial fits to the data points. The dashed green curve is a smoothed fit for Inuit data, as found by Wojciechoski *et al.* (2003).[51]

Summarising the distribution of refractive errors

The foregoing has largely been concerned with factors affecting the comparability of prevalence data. The problems of a patient with low myopia are, however, very different from those of a high myope and the full frequency distribution of refractive error offers much more information than does a single prevalence value extracted from it. To allow prevalences with different cut-offs to be compared, it would be helpful if MSE frequency distribution data was specified in intervals of 0.25 D or even 0.12 D, even though it might be grouped into larger intervals for graphical display. The relative complexity of the full frequency distribution of ametropia, however, raises its own problems when different distributions are to be compared, rather than simple prevalences. Some simplification of the task of comparing different distributions could be achieved, however, if it were possible to adequately describe them by a limited set of parameters. How might this be done?

Mean and standard deviation

In many studies, data on the distributions of refractive errors for the populations considered are not given in full but are summarised in terms of their arithmetic means and standard deviations. It is clear that the latter two parameters alone are of limited value, since the distributions of refractive errors are unlikely to be normal. Although a few authors[17,20,38,52,53] quote values for the skewness and kurtosis of some of their error distributions, in addition to the mean and standard deviation, this suggestion has not been widely adopted, perhaps because it it is difficult to visualise the shape of the distribution from the values of the four parameters.

Nevertheless some useful inferences can be drawn from comparisons of standard deviations. A uniform shift of the refractions of all individuals in the negative direction will affect the means but not the standard deviations. In the much more realistic case where only some individual refractions become more negative, the distribution of errors will broaden and its standard deviation will increase. As an example, consider the data of Lin *et al.*[14] for myopia in Taiwanese school children over the period 1983–2000 inclusive: these data include both mean MSE and its standard deviation for yearly cohorts, as collected in different years. A consistent measurement and analysis method was applied throughout the study, minimising the effects of most of the problems discussed earlier. *Figure 6a* replots the refraction data. It can be seen that at each date the mean refraction of each year group becomes more negative with age and that, as the date advances from 1983 to 2000, it appears that overall refractions become more negative. If we look at the corresponding standard deviations (*Figure 6b*), we can see that both at each fixed date and across dates, the standard deviation tends to increase as the myopia increases, implying that the distributions of refractive error are becoming broader with age, rather than simply shifting in the myopic direction.

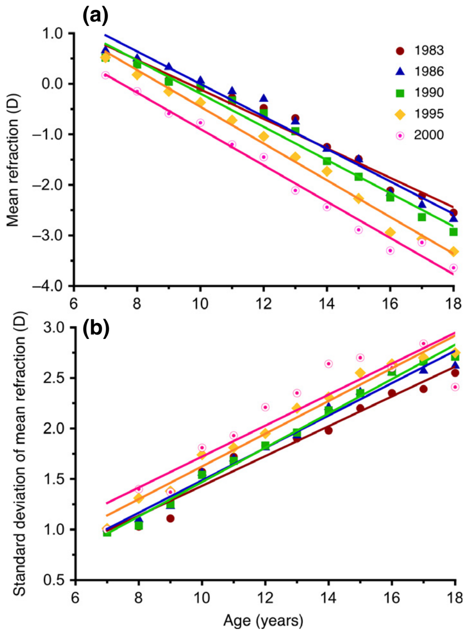

Figure 6. (a) Data on the mean refractions of different age groups of Taiwanese schoolchildren at various dates (b) The corresponding standard deviations (replotted from table 2 of Lin *et al.*[14]). The continuous lines correspond to least square regression fits.

The general relationship between mean refractive error and its standard deviation is illustrated in more detail in *Figure 7*. This shows the standard deviations for each year group at each date, plotted as a function of the corresponding mean refractive error. Rather remarkably, it is evident that standard deviations increase systematically as the mean refractive error becomes more negative, irrespective of the year in which the data were obtained or the year group. Unfortunately, as noted earlier, the distributions of error corresponding to each point are almost certainly never normal, so that their standard deviation gives an incomplete indication of the nature of the distribution. Thus the interpretation of this result is somewhat limited. Nevertheless, the broad implication is that any changes with age or date are not simple myopic shifts of the refractive characteristics of all members of the group, but must involve a larger spread of errors within the distribution i.e. that the errors of some individuals must change more than those of others. We can also infer that, since standard deviations are essentially the same at any level of mean refraction, irrespective of the date, in *Figure 6a* the same general refractive changes may be occurring at progressively earlier ages (i.e. at an accelerated rate) over the period 1983–2000.

We can take these arguments a little further by considering the slope and intercept parameters for the regression line fits to the refractive changes of *Figure 6a*. These are plotted in *Figure 8* as a function of date.

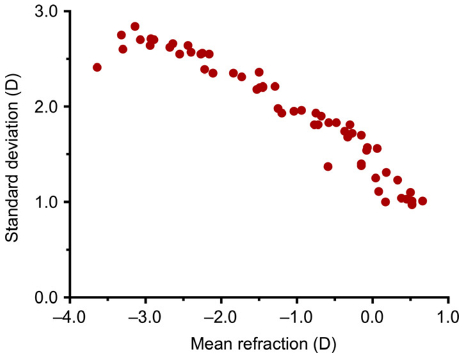

Figure 7. Relationship between the mean refractive error and its standard deviation for each combination of age group and date (plotted using data for 1983–2000 from Lin *et al.*[14]). As the mean error becomes more myopic, the spread of the distribution of errors appears to increase.

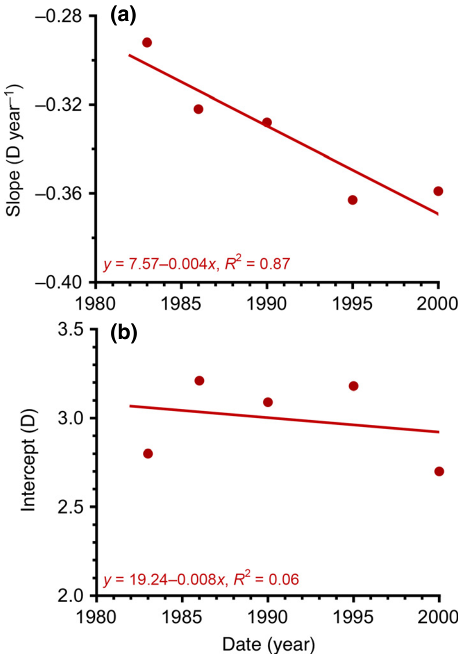

Figure 8. The slope and intercept of regression line fits to the mean refraction/age data of *Figure* 6*a* (Lin *et al.*[14]) as a function of the year in which the data were obtained.

The slopes appear to become increasingly negative as the dates advance i.e. the rates at which myopia develops become higher. However, the intercept does not change significantly, remaining at around 3.0 D. Although dependent on a slightly dubious extrapolation to age zero, the latter result suggests that the refractions in infancy may not have changed over the period of study. Thus, the overall implication is again that the distribution of refractive trends amongst individuals is essentially the same but that all the individual rates of change have been accelerated by a constant factor as the date has advanced.

A similar tendency for the standard deviation of the MSE to increase with age during later childhood was found by Fan *et al.*[54] in a longitudinal study of a group of 108 Hong Kong Chinese primary school children at five and 10 years. When the distributions of MSE were described in terms of means and their standard deviations, at 12 years the mean refraction was more myopic and had a larger SD (mean and SD −0.44 ± 1.72 D compared with +0.77 ± 0.80 D for the 6-year-olds. In fact, the distribution of errors once the children were older (2000) was broader and less leptokurtic (*Figure 9*): indeed, it may be bimodal. It is clear that the refractive errors have changed only for a subset of the children, rather than the whole group. If they were available, it would obviously be instructive to plot the distribution of the individual rates of myopia progression to explore these inter-subject differences in more detail.

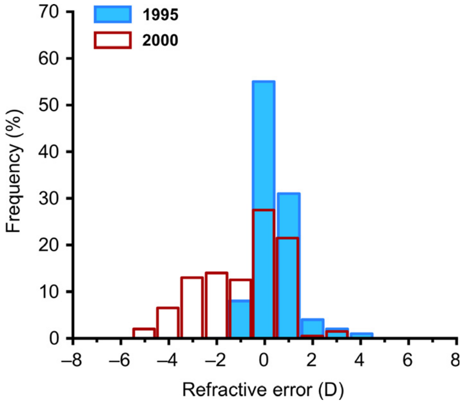

Figure 9. Changes in the refractive error distribution over a 5-year time interval for the same group of Hong Kong children with an initial mean age of 5 years (after Fan *et al.*[53]).

Parametric description of distributions of refractive error

Bigaussian fits

It is clear from the foregoing that, as many others have noted, the use of a mean and a standard deviation to describe the refractive characteristics of a group at any age usually gives an incomplete description of the associated frequency distribution of refractive errors.

In an important article, Flitcroft[16] has pointed out recently that the observed distributions appear to be the result of two main conflicting mechanisms, the first controlling eye growth in infancy so that refraction tends towards emmetropia or low hyperopia, the second during later childhood which leads towards myopia. He gives details of a model of refractive development based on these mechanisms, which, with appropriate adjustment of parameters, leads to good simulations of the observed distributions at different ages. In a further paper, Flitcroft[17] suggests that the failure of some eyes to emmetropise in early childhood, allied to the failure of some emmetropic eyes to maintain emmetropia in later childhood and the teenage years, leads at any age to two distinct populations of eyes. The “emmetropised” population is characterized by a relatively narrow Gaussian (normal) distribution, peaking near emmetropia. In contrast, the “dysregulated” population has a much broader Gaussian distribution and a myopic mean. This model is characterized by five parameters: a mean and a standard deviation (D) for each Gaussian and a figure giving the proportion of individuals contributing to each Gaussian mode.

Rozema and Tassignon[52] recently found, in a non-cycloplegic, cross-sectional study of 1136 healthy, white European eyes, that refractive distributions could be satisfactorily modelled in these terms, with about 60% of the eyes falling into the emmetropic group and 40% in the

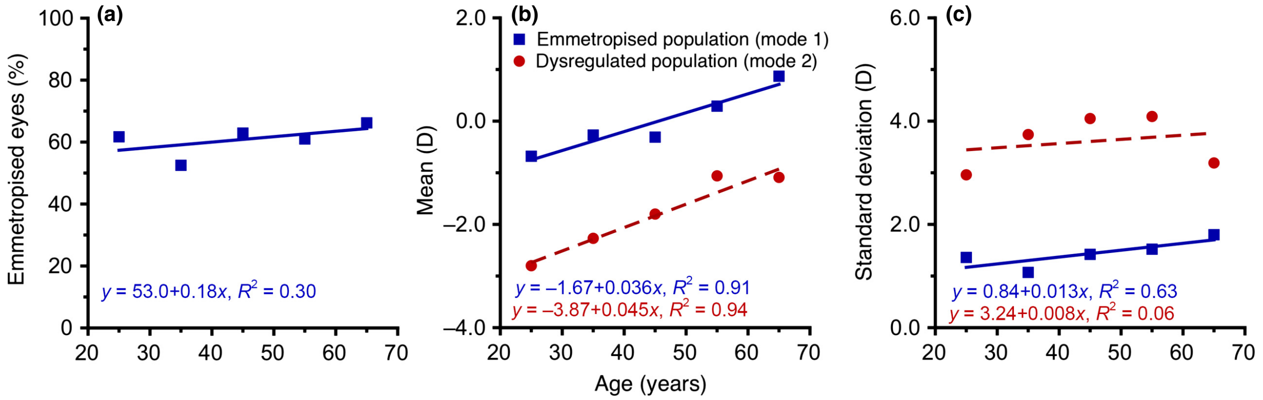

Figure 10. Changes in (a) the percentage of eyes in the "emmetropised" group (b) the means and (c) the standard deviations of the two Gaussians (Mode 1, "emmetropised" and Mode 2, "dysregulated") in the biGaussian approximation to the observed distribution of refractive errors, plotted for 10-year age-groups (i.e. 20–30 years, 30–40 years etc). The blue squares refer to the Mode 1 "emmetropised population". The red circles refer to the Mode 2 "dysregulated" population. The continuous and dashed lines correspond to least square regression fits. Plotted from the data of Rozema & Tassignon[52].

dysregulated group (*Figure 10a*): the fit to the observed distributions was not improved by increasing the number of component Gaussians. When subjects are divided into age groups by decade, the slope of the regression line fit of the percentage of eyes in the "emmetropic" group as a function of age does not differ significantly from zero (*Figure 10a*), so that these proportions change little throughout adult life. Although caution must be exercised when interpreting cross-sectional data, this may imply that there is little interchange between the two groups throughout adult life. *Figure 10b* plots the means and *Figure 10c* the standard deviations of the two component Gaussians as a function of age. As would be expected from their *Figure 4*, the slopes of the regression lines showing the change in means with age in *Figure 10b* differ significantly from zero ($p < 0.05$) but those for the standard deviations (*Figure 10c*) do not. This suggests that although the refractive distribution tends to move in a hyperopic direction in later life, the spread of the errors does not change greatly. Thus the refractions of all eyes must experience broadly similar refractive shifts with age. The hyperopic shift in the means of both components of about 1.6 D over 40 years in *Figure 10b* is compatible with the MSE/age data of *Figure 4*, although Rozema & Tassignon[52] suggest that their cross-sectional data may reflect an "increased prevalence of myopia in young people over the past few decades".

The Ex-Gaussian model

As an alternative to the biGaussian approach, with its five fitting parameters, we have found it useful to fit the empirical distributions, where available, with simpler ex-Gaussian functions. The ex-Gaussian, which is often used in the analysis of response times and fixation durations in reading,[55,56] represents the convolution of a Gaussian (normal) and an exponential function.[54,55] MATLAB-based approaches to determining the relevant parameters using maximum likelihood methods are available.[57] Ex-Gaussian analysis uses only three parameters. These correspond to the location/mean (μ) and the standard deviation (σ) of the Gaussian (normal) distribution, and the mean and the standard deviation (both τ) of the exponential component, which has a rate $\lambda = 1/\tau$. The overall mean of the ex-Gaussian is $\mu + \tau$, and the overall standard deviation is $(\sigma^2 + \tau^2)^{½}$. The skewness is $2\tau^3/(\sigma^2 + \tau^2)^{3/2}$ and the excess kurtosis is $[2(\sigma^2 + 2\tau^2 + 3\tau^4/\rho^2)/(\sigma^2 + \tau^2) - 3]$.

While caution should be used in attributing physiological meaning to this description, it is tempting to suggest that, in relation to Flitcroft's model,[17] the Gaussian component is related to the underlying distribution of errors left after emmetropisation, having a mean that may be age-dependent, and that the exponential may be related to the probability of a particular myopic shift occurring as a function of the magnitude of that shift, although in practice it is known that this is related to the previous refractive history of the individual. By fitting the ex-Gaussian distribution to the distributions of refractive error data, and then comparing the parameter values across conditions (e.g. age groups), we can establish whether differences in overall means are due to a shift in the Gaussian component (μ) and/or to a specific difference in the "myopic tail" (exponential component) of the distribution (τ).

To illustrate this approach, *Figure 11* applies ex-Gaussian fits to data from Kamiya[58] for Japanese boys. It can be seen that in general the fits are reasonable, in spite of the fact that the use of the exponential implies that any refractive shifts are always in the same direction (i.e. that there

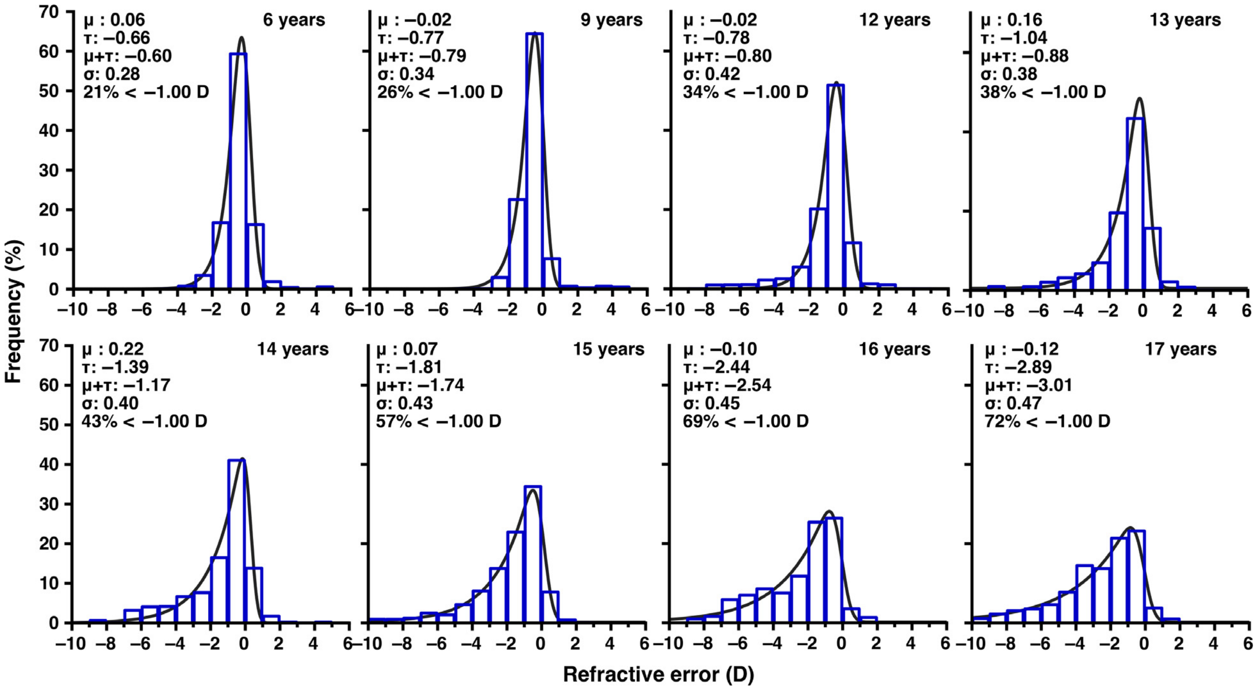

Figure 11. Ex-Gaussian fits to refractive error distributions for Japanese boys of different ages, as found by Kamiya[58] Ex-Gaussian represents the convolution of a Gaussian (normal) and an exponential function and can be characterized by three parameters: the mean (μ) and the standard deviation (σ) of the Gaussian component, and the mean/standard deviation (τ) of the exponential component. A fitting algorithm that minimizes x^2 was used (profit 6.2, Quantom Soft, Switzerland).

are no hyperopic shifts in these cases). While it is obvious that the distributions become broader and that the mean refraction becomes more myopic as the age increases, the changes in fitting parameters give greater insight (*Figure 12*). The underlying Gaussian parameters (μ, σ) show little change with age, but the mean (τ) of the exponential, whose magnitude is related to the extent of the myopic changes in refraction for some individuals, becomes more negative, shifting the overall mean (μ + τ) in the negative direction and making the distribution more skewed in the negative direction.

The weakness of the ex-Gaussian model is that, in contrast to the biGaussian, it can only approximate refractive distributions with a single peak and hence is a less useful descriptor of bimodal distributions.

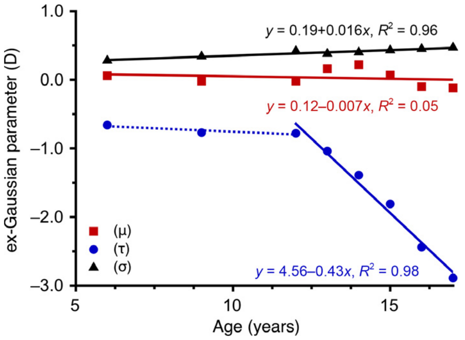

Figure 12. Ex-Gaussian fitting parameters μ (red), σ (black) and τ (blue) from *Figure* 11, plotted as a function of age. The regression-line fits to μ and σ show little change with age but the exponential parameter τ changes systematically during adolescence (>12 years). The continuous lines correspond to least-square regression fits except for τ, where the data are fitted with two lines over different age intervals.

Conclusion

There remains a need for greater standardisation in sampling strategies, refractive measurement procedures and definition of myopia in prevalence studies. In both cross-sectional and longitudinal studies of changes in refraction with age, it is desirable that the distributions of refractive error be considered, together with the distribution of individual rates of refractive change, rather than just the means and standard deviations. If mean refractions at different ages are to be compared, the interpretation of the results should take account of the normal age-dependent trends in refraction. The use of bi-Gaussian or ex-Gaussian fits may be helpful when considering changes in the form of the distribution of refractive errors with age.

Disclosure

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References

1. Edwards MH. The development of myopia in Hong Kong children between the ages of 7 and 12 years: a five-year longitudinal study. *Ophthalmic Physiol Opt* 1999; 19: 286–294.
2. Lin LL, Shih Y, Tsai C *et al.* Epidemiological study of ocular refraction among schoolchildren in Taiwan in 1995. *Optom Vis Sci* 1999; 76: 275–281.
3. Edwards MH & Lam CS. The epidemiology of myopia in Hong Kong. *Ann Acad Med Singapore* 2004; 33: 34–38.
4. Pan CW, Zheng YF, Anuar AR *et al.* Prevalence of refractive errors in a multiethnic Asian population: the Singapore epidemiology of eye disease study. *Invest Ophthalmol Vis Sci* 2013; 54: 2590–2598.
5. Pan CW, Ramamurthy D & Saw SM. Worldwide prevalence and risk factors for myopia. *Ophthalmic Physiol Opt* 2012; 32: 3–16.
6. Vitale S, Sperduto RD & Ferris FL. Increased prevalence of myopia in the United States between 1971–1972 and 1999–2004. *Arch Ophthalmol* 2009; 127: 1632–1639.
7. Young FA, Leary GA, Baldwin WR *et al.* The transmission of refractive errors within eskimo families. *Am J Optom Arch Am Acad Optom* 1969; 46: 676–685.
8. Sorsby A. Transmission of refractive errors within eskimo families. *Am J Optom Arch Am Acad Optom* 1970; 47: 245–246.
9. Young FA. Transmission of refractive errors within eskimo families. *Am J Optom Arch Am Acad Optom* 1970; 47: 246–249.
10. Fledelius HC. Myopia profile in Copenhagen medical students 1996–98. Refractive stability over a century is suggested. *Acta Ophthalmol Scand* 2000; 78: 501–505.
11. Mutti DO & Zadnik K. Age-related decreases in the prevalence of myopia: longitudinal change or cohort effect? *Invest Ophthalmol Vis Sci* 2000; 41: 2103–2107.
12. Park DJ & Congdon NG. Evidence for an “epidemic” of myopia. *Ann Acad Med Singapore* 2004; 33: 21–26.
13. Wensor M, McCarty CA & Taylor HR. Prevalence and risk factors of myopia in Victoria, Australia. *Arch Ophthalmol* 1999; 117: 658–663.
14. Lin LL, Shih YF, Hsiao CK & Chen CJ. Prevalence of myopia in Taiwanese schoolchildren: 1983 to 2000. *Ann Acad Med Singapore* 2004; 33: 27–33.
15. Lam CS, Lam CH, Cheng SC & Chan LY. Prevalence of myopia among Hong Kong Chinese schoolchildren: changes over two decades. *Ophthalmic Physiol Opt* 2012; 32: 17–24.
16. Flitcroft DI. Is myopia a failure of homeostasis? *Exp Eye Res* 2013; 114: 16–24.
17. Flitcroft DI. Emmetropisation and the aetiology of refractive errors. *Eye (Lond)* 2014; 28: 169–179.
18. Sorsby A, Sheridan M, Leary GA & Benjamin B. Vision, visual acuity, and ocular refraction of young men: findings in a sample of 1,033 subjects. *Br Med J* 1960; 1: 1394–1398.
19. Stromberg E. Refraktion und Achsenlänge des menslichen Auges. *Acta Opthalmol* 1936; 14: 281–293.
20. Stenstrom S. Investigation of the variation and the correlation of the optical elements of human eyes. *Am J Optom Arch Am Acad Optom* 1948; 25: 218–232, 286–298, 340–350, 388–397, 438–449, 496–504.
21. Bullimore MA, Fusaro RE & Adams CW. The repeatability of automated and clinician refraction. *Optom Vis Sci* 1998; 75: 617–622.
22. Goss DA & Grosvenor T. Reliability of refraction–a literature review. *J Am Optom Assoc* 1996; 67: 619–630.
23. Pesudovs K, Parker KE, Cheng H & Applegate RA. The precision of wavefront refraction compared to subjective refraction and autorefraction. *Optom Vis Sci* 2007; 84: 387–392.
24. Kleinstein RN, Jones LA, Hullett S *et al.* Refractive error and ethnicity in children. *Arch Ophthalmol* 2003; 121: 1141–1147.
25. Fledelius HC. Myopia prevalence in Scandinavia. *Acta Ophthalmol Suppl* 1988; 185: 44–50.
26. Curtin B. Topics to be considered when establishing standards for clinical myopia studies. *Acta Ophthalmol Suppl* 1998; 185: 61.
27. Saw SM. A synopsis of the prevalence rates and environmental risk factors for myopia. *Clin Exp Optom* 2003; 86: 289–294.
28. Framingham Offspring Study Group. Familial aggregation and prevalence of myopia in the Framingham Offspring Eye Study. *Arch Ophthamol* 1996; 114: 326–332.
29. Katz J, Tielsch JM & Sommer A. Prevalence and risk factors for refractive errors in an adult inner city population. *Invest Ophthalmol Vis Sci* 1997; 38: 334–340.
30. Lin L-K, Shih Y-F, Lee Y-C, Hung P-T & Hou P-K. Changes in ocular refraction and its components among medical students - a 5-year longitudinal study. *Optom Vis Sci* 1996; 73: 495–498.
31. Kinge B & Midelfart A. Refractive changes among Norwegian university students - a three-year longitudinal study. *Acta Ophthalmol* 1999; 77: 302–305.
32. Lithander J. Prevalence of myopia in school children in the Sultanate of Oman: a nation-wide study of 6292 randomly selected children. *Acta Ophthalmol* 1999; 77: 306–309.
33. Montes-Mico R & Ferre-Blasco T. Distribution of refractive errors in Spain. *Doc Ophthalmol* 2000; 101: 25–33.
34. Loman J, Quinn GE, Kamoun L *et al.* Myopia and its progression in third-year law students. *Ophthalmology* 2002; 109: 1032–1038.
35. Quek TPL, Chua CG, Chong CS *et al.* Prevalence of refractive errors in teenage high school students in Singapore. *Ophthal Physiol Opt* 2004; 24: 47–55.

36. Eye Diseases Study Group. The prevalence of refractive errors among adults in the United States, Western Europoe, and Australia. *Arch Ophthalmol* 2004; 122: 495–505.
37. Onal S, Toker E, Akingol Z *et al.* Refractive error of medical students in Turkey: one year follow-up of refraction and biometry. *Optom Vis Sci* 2007; 84: 175–180.
38. French AN, O'Donoghue L, Morgan IG, Saunders KJ, Mitchell P & Rose KA. Comparison of refraction and ocular biometry in European Caucasian children living in Northern Ireland and Sydney, Australia. *Invest Ophthalmol Vis Sci* 2012; 53: 4021–4031.
39. Lv L & Zhang Z. Pattern of myopia progression in Chinese medical students: a two-year follow-up study. *Graefes Arch Clin Exp Ophthalmol* 2013; 251: 163–168.
40. Pan CW, Dirani M, Cheng C-Y, Wong T-Y & Saw S-M. The age-specific prevalence of myopia in Asia: a meta-analysis. *Optom Vis Sci* 2015; 92: 258–266.
41. Charman WN. Visual standards for driving. *Ophthalmic Physiol Opt* 1985; 5: 211–220.
42. Drasdo N & Haggerty CM. A comparison of the British number plate and Snellen vision tests for car drivers. *Ophthalmic Physiol Opt* 1981; 1: 39–54.
43. Saunders H. Age-dependence of human refractive errors. *Ophthalmic Physiol Opt* 1981; 1: 159–174.
44. Slataper FJ. Age norms of refraction and vision. *Arch Ophthalmol* 1950; 43: 468–481.
45. Saunders H. A longitudinal study of the age-dependence of human ocular refraction–I. Age-dependent changes in the equivalent sphere. *Ophthalmic Physiol Opt* 1986; 6: 39–46.
46. Fledelius HC. Refraction and eye size in the elderly. A review based on literature, including own results. *Acta Ophthalmol (Copenh)* 1988; 66: 241–248.
47. Hirsch MJ. The chnages in refraction between the ages of 5 and 14 - theortetical and practical considerations. *Am J Optom Arch Am Acad Optom* 1952; 29: 445–459.
48. Hirsch MJ. Changes in refractive stae after the age of forty-five. *Am J Optom Arch Am Acad Optom* 1958; 35: 229–237.
49. Sorsby A, Benjamin B & Sheridan M. Refraction and its components during growth of the eye from the age of three. *Spec Rep Ser Med Res Counc* No. 301. HMSO:London, 1961.
50. Lavery JR, Gibson JM, Shaw DE & Rosenthal AR. Refraction and refractive errors in an elderly population. *Ophthalmic Physiol Opt* 1988; 8: 394–396.
51. Wojciechowski R, Congdon N, Anninger W & Broman AT. Age, gender, biometry, refractive error, and the anterior chamber angle among Alaskan eskimos. *Ophthalmology* 2003; 110: 365–375.
52. Rozema JJ, Tassignon MJ & for Evicr.net PGSG. The bigaussian nature of ocular biometry. *Optom Vis Sci* 2014; 91: 713–722.
53. Watanabe S, Yamashita T & Ohba N. A longitudinal study of cycloplegic refraction in a cohort of 350 Japaneses schoolchildren, Cycloplegic refraction. *Ophthalmic Physiol Opt* 1999; 19: 22–29.
54. Fan DS, Cheung EY, Lai RY, Kwok AK & Lam DS. Myopia progression among preschool Chinese children in Hong Kong. *Ann Acad Med Singapore* 2004; 33: 39–43.
55. Balota DA & Yap MJ. Moving beyond the mean in studies of mental chronometry: the power of response time distributional analyses. *Curr Dir Psychol Sci* 2011; 20: 160–166.
56. Ratcliff R. Group reaction time distributions and an analysis of distribution statistics. *Psychol Bull* 1979; 86: 446–461.
57. Lacouture Y & Cousineau D. How to use MATLAB to fit ex-Gaussian and other probability functions to a distribution of response times. *Tutor Quant Methods Psychol* 2008; 4: 35–45.
58. Kamiya S. Analysis of school myopia using the Nidek Auto-Refractometer AR 3000. Part 2. Observation of frequency distribution of pupil refraction. *Folia Ophthalmol Jpn* 1984; 35: 1755–1769.