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Nature and Nurture: the complex genetics of myopia and refractive error

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Abstract

The refractive errors, myopia and hyperopia, are optical defects of the visual system that can cause blurred vision. Uncorrected refractive errors are the most common causes of visual impairment worldwide. It is estimated that 2.5 billion people will be affected by myopia alone within the next decade. Experimental, epidemiological and clinical research has shown that refractive development is influenced by both environmental and genetic factors. Animal models have demonstrated that eye growth and refractive maturation during infancy are tightly regulated by visually-guided mechanisms. Observational data in human populations provide compelling evidence that environmental influences and individual behavioral factors play crucial roles in myopia susceptibility. Nevertheless, the majority of the variance of refractive error within populations is thought to be due to hereditary factors. Genetic linkage studies have mapped two dozen loci, while association studies have implicated more than 25 different genes in refractive variation. Many of these genes are involved in common biological pathways known to mediate extracellular matrix composition and regulate connective tissue remodeling. Other associated genomic regions suggest novel mechanisms in the etiology of human myopia, such as mitochondrial-mediated cell death or photoreceptor-mediated visual signal transmission. Taken together, observational and experimental studies have revealed the complex nature of human refractive variation, which likely involves variants in several genes and functional pathways. Multiway interactions between genes and/or environmental factors may also be important in determining individual risks of myopia, and may help explain the complex pattern of refractive error in human populations.

Keywords

myopia; refractive errors; genetics; epidemiology

Introduction

Ocular refractive errors are optical defects in which images of viewed objects do not coincide with the retinal plane, causing blurred vision. There are two forms of spherical refractive errors: myopia and hyperopia (figure 1). Because myopia has been the most widely studied refractive error, it is the primary focus of this review. Ocular refraction, defined as a quantitative measurement of the magnitude of refractive errors, will also be discussed when applicable.

Refractive errors are the most widespread human eye disorders (1). Myopia affects more than one in four people over age 40 in the United States and Western Europe while visually

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significant hyperopia afflicts about ten percent of individuals in the same age group (2). In some urban areas in East Asia, the prevalence of myopia among teenagers and young adults exceeds 70% (3–5). By the year 2020, it is estimated that 2.5 billion people—one third of the world’s population—will be affected by myopia alone (2). Myopia is a risk factor for a number of ocular conditions including: peripheral retinal degenerations; age related cataracts; glaucoma; and choroidal neovascularization (6). Pathological myopia is characterized by a progressive elongation of the eye globe accompanied by potentially-blinding degenerative changes in the retina and choroid (7).

Although they can usually be corrected by optical means or with refractive surgery, uncorrected or poorly-corrected refractive errors are the most common causes of visual impairment in both industrialized and developing nations (1,8–11) ENREF 6. Worldwide, more than 150 million people are estimated to be visually impaired because of uncorrected refractive error, of which 8 million are functionally blind (12). The global economic productivity loss due to visual impairment from uncorrected refractive error has been estimated at \$268 billion (13).

It is generally accepted that the distribution of refractive errors in human populations is determined by complex interactions of biological, environmental and behavioral factors (14,15). Though numerous risk factors have been studied over decades of epidemiological and experimental research, a comprehensive mechanistic framework for refractive error development in humans remains elusive.

Anatomical and optical basis of refractive errors

Clear vision requires an optical system that properly focuses images of viewed objects on the eye’s sensory tissue, the retina. This is accomplished through a precise coordination of the refractive components to align of the eye’s focal point with the retinal plane. Any departure from a coincidence between the focal point and the retina will result in reduced image contrast at the retina and cause subjectively blurred vision. Myopia (or nearsightedness) occurs when distant objects focus anteriorly to the retina. Experimental myopia models and epidemiological data have shown that myopia is the result of a disproportionate elongation of the posterior segment of the eye, whose physical boundary is provided by the fibrous sclera (figure 1). In contrast, hyperopia (or farsightedness) is due to a relatively short eye for which the focal point is located posterior to the retina. Myopia and hyperopia together form the (spherical) refractive errors or ametropias.

The severity of refractive errors is typically quantified in terms of the optical power of a lens (in vergence diopters (D)) necessary to correct the optical defect of the myopic or hyperopic eye. By convention, myopia is quantified with negative values on the dioptric scale while hyperopia is designated by positive numbers. Most studies of myopia or hyperopia define these phenotypes as binary traits using somewhat arbitrary cutoffs of the underlying refractive values. These thresholds typically range between -0.5 D and -1 D for mild myopia, -5 D to -6 D for high myopia, and -10 D or less for extreme myopia. The term “pathological myopia” is also commonly used and should be reserved for cases of high myopia characterized by extreme, progressive, ocular growth accompanied by potentially visually-devastating sequelae.

Environmental influences on refractive error

Both biological (nature) and environmental (nurture) sources of refractive variation are likely to be present in most human populations. A complete account of the research into the etiology of refractive error is beyond the scope of this review. We present below some of the

major findings supporting environmental and/or genetic effects on refractive development. A summary of these and other contributors to refractive variation are outlined in table 1.

Animal models of experimental myopia

A large body of evidence from over three decades of animal studies has shown that manipulations of the visual environment can induce predictable changes in scleral growth and lead to experimentally-induced refractive errors. In the late 1970s, three seminal papers reported that variations in the early visual experience of animal models could lead to altered eye growth and, as a result, to changes in ocular refraction (16–18). Specifically, visual form deprivation (produced by eyelid suture or via translucent occluders) induced seemingly unconstrained ocular elongation and corresponding myopic refractive changes in chick (17), tree shrew (16), and macaque monkey (18) (figure 1, bottom right). Additionally, studies in children whose vision had been disrupted during infancy confirmed that form deprivation-induced myopia can also occur in humans during susceptible periods of early ocular development (19–21).

These early animal studies spawned research into experimentally-induced refractive errors which lead to the development of a variety of vertebrate animal models, environmental manipulations and refractive error control paradigms. One of the fundamental insights of this important body of work was that changes in ocular growth patterns in a number of vertebrate species can be caused not only by visual form deprivation, but also by optical defocus (22–25). Specifically, the introduction of negatively-powered lenses in front of normally developing chick (24,25) and primate (22,23,26) [ENREF 18](#) eyes can potentiate compensatory increases in the rate of eye growth, and cause relative myopia (compared to untreated eyes). Positive lenses, on the other hand, tend to arrest eye growth during early visual development and cause relative hyperopia.

Animal models have provided invaluable insight into the complex biological processes likely to be involved in human ocular growth and refractive development. The basic model behind refractive control during infancy involves a visually-driven feedback mechanism that modulates eye growth. In this model, environmental exposures trigger a visually-evoked signaling cascade that originates in the retina, passes through the vascular choroid (figure 1, top right), and ultimately initiates scleral remodeling (see (27–31) for reviews). The sclera is a rigid, highly-organized, connective tissue whose gene-expression profile is similar to that of cartilage (32) and is comprised of extracellular matrix (ECM) and matrix secreting fibroblasts (33). Hence, the biological mechanisms involved in refractive error are thought to ultimately act through differential effects on scleral growth via active ECM remodeling.

Age-dependent changes in refractive error

Epidemiologic data show that refractive development is a dynamic process and that refractive changes occur throughout life at variable rates. Data from human and animal studies show a highly variable distribution of refractive error during the neonatal period, typically centered in the hyperopic ranges (26,34,35). Though the human eye undergoes rapid growth during early childhood--increasing in length from approximately 18 mm at birth to 22–23 mm at three years of age--the variability of refractive error decreases progressively during this period (36–39). At age 5, most children are functionally emmetropic (39–42). This tightening of the standard deviation of refractive error during infancy and early childhood is postulated to be due to the process of “emmetropization” in which eye growth is regulated by a visually-guided feedback mechanism. After the early period of rapid eye growth, the human eye undergoes slow refractive changes that often culminate in the development of myopia (43). During school years, the distribution of refractive errors gradually shifts towards more myopia with increasing age. Corneal

curvature appears to remain relatively stable after age 6, and therefore does not play an important role in juvenile and adult-onset myopia (44). Instead, human myopia is largely the result of age-dependent increase in ocular axial length (36,45,46), corroborating evidence from animal myopia models. Although the rate of refractive change during late childhood can vary between populations and ethnicities, the incidence of myopia increases progressively from pre-school years and generally reaches its zenith around 9–12 years of age (43,47–50). By early adulthood, the rate of change in ocular refraction tends to decline and the prevalence of myopia stabilizes. During middle age (roughly between age 40 and 60), the prevalence of myopia gradually declines and mean refractive errors become more hyperopic (51–53).

Ethnic and geographic influences on refractive error

It is inherently problematic to make rigorous between-study comparisons of refractive error incidence and prevalence data because of a wide variability of sampling methodology, examination methods and diagnostic criteria utilized. The Refractive Error Study in Children (RESC) (54) was designed, in part, to assess the prevalence of refractive errors in 5 to 15 year-old children in various geographical regions while using standardized sampling, examination protocols, and diagnostic criteria. Surveys were conducted at eight locations: rural Nepal (55); rural and urban zones in India (56,57) and China (5,58); a semi-urban area in Durban, South Africa (59); and suburban districts of Santiago, Chile (60) and Kuala Lumpur, Malaysia (61). Results showed very low prevalences of myopia among 5 year-olds across study sites--ranging from 0.45% in rural Nepal (55) to 4.29% in urban New Delhi, India (56). However, the prevalence of refractive errors varied widely among fifteen year-olds (figure 2): the prevalence of myopia was 0.79% in rural Nepal (55); 48.7% in rural China (58); and 79.9% in urban Liwan District, Guangzhou, China (5). This series of studies clearly shows a wide variation in the age-specific prevalence of refractive errors between geographic regions. Interestingly, Chinese and Indian children living in urban areas showed significantly greater rates of myopia than their ethnicity-matched counterparts from more rural regions (5,56–58). A higher prevalence of myopia in urban areas has also been documented in other populations (62–65). These regional differences in the prevalence of myopia argue in favor of a strong environmental influence on refractive development.

The RESC survey of Malaysian children showed a considerably higher prevalence of myopia among ethnic Chinese than in children of Malay, and Indian ancestries (61). A similar excess risk of myopia among ethnic Chinese subjects has been observed in male military recruits (4) and school children (66) in Singapore. High risks of myopia among children of East Asian ancestry have also been reported in Australia (67), the United States (68) and the United Kingdom (69). Although estimates from individual studies vary, urban populations in East Asia show consistently high rates of myopia (often exceeding 80%)(42). Whether this is due to inter-ethnic differences in the genetic predisposition to myopia or to culture-specific environmental influences remains uncertain.

The epidemiological study of genetically or culturally isolated populations may help provide important clues about the multifactorial etiology of refractive error. For example, Orthodox Jewish communities are thought to suffer disproportionately from myopia (70,71). In a study of ocular refraction in Israel, Zylbermann et al. (71) found that teenage Jewish boys who attended Orthodox schools were, on average, 2.4 D more myopic than boys who were educated in secular school (mean refractive error = -2.9 for Orthodox school and -0.50 D for general school). In contrast, the refractive error distribution was no different between girls educated in Orthodox schools and girls who attended general schools (mean refractive error = -0.90 in both groups). Orthodox boys and girls attend separate schools with different curricula, with boys' schools emphasizing intense and prolonged study of religious texts. The authors postulated that the intensive visual demand associated with the religious

education of Orthodox males is likely responsible for high rates of myopia in the Jewish Orthodox community. Interestingly, two genetic loci for myopia susceptibility (72)(MYP6) and ocular refraction (73)(MYP14) originally identified in American Orthodox Jewish families have been replicated in linkage studies in Midwestern American pedigrees (74) (MYP6), the Old Order Amish (75)(MYP14), and in an international consortium of high-grade myopia (76)(MYP6 and MYP14).

Environmental and behavioral risk factors for refractive error

There is accumulating epidemiological evidence that the prevalence of myopia has increased appreciably in many areas across the globe within the last two-to-three decades (3,77–79). This secular trend is most marked in East Asia, where myopia now affects a significant proportion (over 80% in some areas) of young adults. Using a series of nationwide surveys, Lin et al. documented a significant increase in the prevalence of myopia among Taiwanese school children between 1983 and 2000 (3). The estimated prevalences of myopia at ages 7, 12, 15 and 18 were: 5.8%, 36.7%, 64.2% and 74% in 1983; and 21%, 61%, 81% and 84% in 2000. Moreover, the prevalence of high myopia (worse than -6 D) among 18 year-old students had increased from 10.9% in 1983 to 21% in 2000 (3). Matsumura and Hirai showed an increased prevalence of myopia, and a corresponding shift in mean refractive error towards myopia, among Japanese school children over a 12-year period from 1984 to 1996 (77). Nevertheless, the study was conducted in selected schools so their results cannot necessarily be extrapolated to the general Japanese population. The rate of myopia also appears to be increasing in some populations outside of East Asia. Vitale et al. estimated the prevalence of myopia in 12 to 54 year-old Americans to have increased from 25% to 41.6% between 1971–72 and 1999–2004 (79). Similarly, in a retrospective study of over 900,000 Israeli military recruits, Bar Dayan documented significant increases in the prevalence of high, moderate, and low myopia between 1990 and 2002 (78). Because the genetic makeup of these populations has not changed within this short time span, it is unlikely that genetic factors played a role in these trends.

In addition to documenting significant geographic and ethnic differences in refractive error distribution, epidemiological investigations have shown correlations between a variety of environmental exposures and the risk of myopia (table 1). For instance, population-based studies have reported associations between myopia and higher socioeconomic status (80) and greater levels of educational attainment (81–86). High prevalences and progression rates of myopia have been observed in individuals in visually intensive occupations such as clinical microscopists (87), carpet weavers (88) and visual display terminal workers (89). Within the context of the myopization process, education, socioeconomic status, and occupation are generally considered to be indirect surrogates for more proximal risk factors such as near-work visual demand and other unmeasured environmental variables. Studies of the effect of reading have attempted to show a more direct relationship between myopia and near work activity. Saw et al. found that myopic schoolchildren in China reported spending more time reading than non-myopic children (62). In a separate study, the same group reported that the number of books read was a better predictor of higher myopia among 7–9 year-olds than the time spent reading (90). Mutti et al. reported that children with myopia spent significantly more time studying, more time reading, and less time playing sports than non-myopic children (91). In a cross-sectional investigation of 12 year-old Australian school children, Ip et al. found no significant relationships between myopia and time spent in near work. However, they showed significant associations of myopia with close reading distance and sustained, continuous, reading (92). Studies on the effect of reading on the rate of progression of myopia have provided conflicting results. In a study of Singapore school children, near work was not associated with worsening myopia (93). On the other hand,

myopic children in Finland who spent more time reading had faster rates of myopia progression (94).

The relationship between reading and near work activity and myopia susceptibility is complex and still poorly understood. Estimates of exposure to near work are subject to considerable measurement error and are prone to bias in retrospective studies. Effect estimates may vary depending on the unit of measurement chosen (i.e., intensity, duration, reading distance or cumulative dose), outcome definitions (myopia, refractive error, rates of progression), or the ages, ethnicities and social circumstances of study subjects. These discrepancies in study characteristics can yield inconsistent results. Moreover, the current ubiquity of technologies such as computers, cellular and smart phones, and gaming devices has added a layer of complexity to the near work question. Indeed, it could be argued that the recent increase in myopia prevalence in East Asia reported in some studies may be the result of a steady rise in the use of modern electronic devices over the past three decades. Nevertheless, a direct link between the utilization of electronic devices and myopia development has yet to be convincingly established and future studies should attempt to validate and quantify this relationship.

While excessive reading or near work activity increase the risk for myopia, other environmental factors (such as participation in sports and time spent outdoors) have shown protective relationships. Recent studies have shown that time spent outdoors and participation in outdoor sports during childhood is associated with a decreased risk of myopia (95–97). Moreover, the beneficial effect of outdoor activity appears not to be the result of a concomitant reduction in near work. There is also evidence that genetic factors may interact with outdoor activity on the risk of myopia. Jones et al. (95) have shown that the inverse relationship between outdoor activity and myopia development may be limited to children with a strong familial predisposition to myopia (i.e., children with 2 myopic parents compared to children with either no or one myopic parent).

Genetic influences on refractive error

Heritability and familial aggregation of refractive errors

While behavior and environment play important, if not entirely elucidated, roles in refractive development, it has been convincingly established that heritable (presumably genetic) factors are also important in ocular refraction. Heritability studies have been conducted in a number of populations using twin data (98–101), as well as in sibship and nuclear family study designs (102–105). These reports provide consistently high heritability estimates for ocular refraction ranging from 50% to more than 90%.

Familial aggregation studies have estimated sibling recurrence risks (λ_s) of common forms of refractive errors to range from 2 to 5.61 for myopia, and 1.58 to 4.87 for hyperopia (102,103,106–108). More extreme refractive errors show even greater familial aggregation than do milder forms (107,109). Moreover, children of myopic parents tend to have longer eyes (110) and are more likely to develop myopia during childhood or adolescence (111–113). Segregation analyses of population based samples are consistent with a complex inheritance pattern for ocular refraction involving several genes and/or shared environmental factors (114,115).

The strong familial effects for refraction phenotypes (as evidenced by high heritabilities and strong familial aggregation) are present across populations with varying underlying distributions of refractive error. This observation is consistent with the hypothesis that environmental influences may drive regional and ethnic differences in refractive distribution, but that within-population variation is largely due to genetic factors. Whether

genes and environment contribute independently to the total phenotypic variance within populations, or whether gene-environment statistical interactions also play a role has remained largely unexplored in population genetic studies.

Syndromic refractive errors

Familial refractive errors can occur in simple (non-syndromic) forms or can be accompanied by other systemic or ocular abnormalities. Syndromic refractive errors are generally monogenic or oligogenic and can occur within a wide spectrum of clinical presentations. Myopia has been reported in a number of ocular syndromes including: X-linked and autosomal recessive congenital stationary night blindness (CSNB; OMIM 310500); X-linked retinitis pigmentosa 2 (RP2; OMIM 312600); and X-linked Bornholm eye disease (OMIM 310460). The myopia in X-linked ocular syndromes appears to be secondary to mutations in loci involved in retinal photoreceptor function (NYX, RP2, MYP1). Myopia can also be a characteristic feature in heritable connective tissue disorders such as: Knobloch syndrome (OMIM 267750); Marfan syndrome (OMIM 154700); and Stickler syndrome (type 1, OMIM 108300; type 2, OMIM 604841). Knobloch syndrome has been associated with mutations in COL18A1 whereas Marfan syndrome is due to a defect in the fibrillin-1 gene (FBN1). These loci have not been shown to be associated with common forms of refractive error. Stickler syndrome is a phenotypically heterogeneous condition characterized by ocular abnormalities (congenital vitreous defects with myopia and/or retinal detachment) variously accompanied by auditory, musculoskeletal, craniofacial and cardiac defects. Type 1 and type 2 Stickler syndrome are caused by mutations in COL2A1 and COL11A1, respectively (116). Interestingly, two studies (117,118) have independently reported statistical associations of simple myopia phenotypes with a COL2A1 polymorphism (rs1635529), suggesting that this gene, which has been implicated in a wide variety of chondrodysplasias (OMIM 120140), may also be involved non-syndromic refractive errors.

Genetic linkage studies of myopia and ocular refraction

The first genetic locus for non-syndromic high myopia (MYP2) was mapped in 1998 to 18p11.31 by Young and her collaborators (119). A number of groups have since reported significant linkage of refractive phenotypes to several independent genetic loci; the Online Mendelian Inheritance in Man (OMIM) database (<http://www.ncbi.nlm.nih.gov/omim>) currently lists 16 named loci (MYP2-MYP17) for non-syndromic high myopia, common myopia or ocular refraction, distributed among 13 chromosomes (MYP1 (120) was mapped in a syndromic form of X-linked recessive myopia). At least 7 loci for refractive phenotypes (MYP1, MYP3, MYP6, MYP11, MYP12, MYP14 and MYP17) have been successfully replicated in independent linkage datasets (74–76,121–125).

Familial linkage studies highlight the heterogeneous genetic etiology of refractive errors. Familial refractive errors can exist in simple Mendelian forms (119,126), be features of systemic (7,127) or ocular (120) syndromes, or follow complex familial transmission patterns (114). Many loci for refraction traits were identified in families who segregated high myopia consistent with autosomal-dominant modes of transmission (119,123,128–132). Other loci were mapped using either binary-trait or quantitative-trait linkage analyses of milder refractive errors with complex inheritance (72,73,122,124,133,134). Though differences in phenotype definitions, modes of inheritance, and ascertainment criteria between studies limit the generalizability of linkage results, replication of linkage signals do suggest some etiological overlap. Moreover, we believe that familial linkage studies will remain important in dissecting the complex genetics of human refractive error, particularly as the rapid technological advances will allow for affordable sequencing of genomic regions under linkage peaks.

Genetic association studies of refraction phenotypes

Candidate-gene association studies—Numerous functional and positional candidate genes have been queried in genetic association studies of refractive traits. Table 2 summarizes results of studies that reported statistically significant associations to myopia or ocular refraction. Positive associations have been reported for variants in genes known to be involved in extracellular-matrix (ECM) growth and remodeling pathways. These include genes that code for a variety of extracellular constituents including: collagens (COL2A1 (117,118), COL1A1 (118)); transforming growth factors (TGFB1 (135), TGFB2 (136), TGIF1 (137)); the hepatocyte growth factor (HGF(138–140)) and its receptor (CMET(141)); insulin-like growth factor (IGF1 (142,143)); matrix metalloproteinases (144,145) (MMP1, MMP2, MMP3 and MMP9); and the proteoglycan lumican (LUM(146–148)). Figure 3 shows a first-order biological interaction network for the refraction-associated genes in table 2 (genes that do not interact directly with other genes in the network were omitted for clarity). The biological network in figure 3 was generated using the “direct interactions” network building algorithm implemented in the MetaCore software suite (GeneGo software Inc., St. Joseph, MI), which utilizes a database derived from manually-curated scientific literature on proteins and small molecules. Of particular interest is the relationship between these gene products and the collagens, which constitute over 90% of the mammalian sclera (33,149,150). As has been noted above, the sclera has been shown to undergo active growth and remodeling in animal myopia models. Hence, these association data support experimental results and provide strong evidence that the genetic basis for human refractive error is partially explained by variations in genes that directly affect ECM composition in scleral tissue, leading to differential rates of ocular enlargement and differences in susceptibility to myopia. In this partial model of refractive development, genetic variants that directly or indirectly increase ECM degradation in response to myopiagenic signals would be expected to increase the rate of eye growth and lead to relative myopia.

To date, the majority of positive candidate gene associations have been reported for high myopia (table 2). At least two of these genes, HGF (140) and COL2A1 (118), have also shown associations to milder refraction phenotypes (117,138,139). These results, and recent studies that reported genetic associations between ocular refraction and polymorphisms in matrix metalloproteinase genes (144,145)(MMP1, MMP2, MMP3 and MMP9), suggest that common biological pathways may underlie extreme myopia and milder cases of refractive error. Matrix metalloproteinases are a major group of zinc-dependent enzymes that regulate cell-matrix composition by cleaving a number of ECM constituents (151). Importantly, MMPs interact biologically with substrates of genes that have shown to be related to refractive phenotypes in association studies (table 2, figure 3). Although the simplified network presented in figure 3 is undoubtedly incomplete and represents only one potential pathway for refraction control, it does illustrate the complex relationships between genes presumed to be involved in human refractive variation, as well as how variations within these genes may interact within a common mechanistic framework.

Candidate region and genomewide association studies—Recent candidate-region (152) and genomewide association studies (GWAS) (153–155) have uncovered additional polymorphisms putatively involved in refractive regulation. These “hypothesis-free” studies have yielded genetic associations that offer novel mechanisms for the molecular basis of refractive development in human populations.

Surprisingly, two studies have implicated mitochondria-mediated cell death as a possible mechanism in ocular refraction (152,155). Using multimarker fine-scale linkage disequilibrium methods, Andrew et al.(152) showed statistical association of refractive error to loci centered on three genes on chromosome 3q: MFN1; PSARL (or PARL); and

SOX2OT. Nakashiki et al.(155) identified a polymorphism (rs577948) at 11q24.1 adjacent to the BLID gene that was associated with an elevated risk of pathological myopia (odds ratio=1.37) in a Japanese group. MFN1, PSARL and BLID are expressed in mitochondria; PSARL and BLID are involved in mitochondrial-led apoptosis, and MFN1 is involved in mitochondrial fusion. The mechanism by which mitochondrial programmed cell death can lead to myopia has not been elucidated and this pathway should be validated in additional studies. Nevertheless, these studies offer a novel mechanism for the genetic etiology of refractive error and a promising avenue for future experimental studies of myopia based on mitochondria-regulated cell apoptosis.

In a recent multi-phase GWAS of European-derived populations, Hysi et al. identified several polymorphisms in a region at 15q25 near the RASGRF1 gene in strong association with ocular refraction (153). Their reverse transcriptase experiments also showed RASGRF1 to be highly expressed in human retina. RASGRF1 expression is regulated by muscarinic receptors (156) and retinoic acid (157), both of which provide putative biological mechanisms for refractive control. Anti-muscarinic agents are effective in preventing ocular elongation in animal myopia models (158,159) and have been employed to reduce myopia progression in human clinical trials (160–162). Moreover, Lin et al.(163), reported that polymorphisms in the muscarinic acetylcholine receptor 1 gene (CHRM1) were associated with high myopia in a Taiwanese population. Retinoic acid is differentially expressed in eyes of chicks, and eutherian mammals (164,165) during experimental induction of myopia, and has been shown to induce increased MMP-2 activity in mineralizing chicken chondrocyte cultures (166) [ENREF 102](#). Hence, though RASGRF1 has not previously been investigated in myopia studies, it may influence ocular growth and refraction through complex biological interactions with a number of substrates known to be involved myopization.

In a companion paper to Hysi et al.(153), Solouki and collaborators mapped a susceptibility locus for refractive errors to an intergenic region at 15q14 (154). The most significant association signal was found for a polymorphism in a putative regulatory region near the genes GJD2 and ACTC1, both of which are expressed in the retina (154). GJD2 encodes a neuron-specific protein (connexin36) that is found in retinal photoreceptors, amacrine and bipolar cells. Connexin36 is essential in the transmission of rod-mediated visual signals in the mammalian retina (167,168). Evidence of photoreceptor-mediated susceptibility to myopia has previously been noted in rare X-linked disorders in which cone and/or rod function is disrupted (169–174). To our knowledge, however, the association of a variant near GJD2 is the first evidence of a possible role for modulators of retinal visual signals in susceptibility to common refractive errors.

Summary

We have shown that ocular refraction is a complex phenotype that is influenced by both environmental factors and genetic predisposition. Numerous lines of evidence from experimental myopia models and epidemiological studies have demonstrated that environmental exposures play crucial roles in ocular growth and refractive development. The precise biological mechanisms through which the environment influences ocular refraction in humans are, however, still a matter of debate. It is likely that exogenous variables interact with heritable factors to modulate eye growth during ocular development.

The evidence in favor of a role for genetic predisposition in refractive development is also convincing. A number of linkage studies have mapped almost 20 loci for high myopia, moderate myopia, and refraction as a quantitative trait. Genetic association investigations have identified variants in at least 25 genes putatively involved in ocular refraction.

However, few positive association results have been convincingly replicated in independent samples, and refractive error susceptibility alleles identified to date are generally estimated to have low or modest effect sizes. This implies that most genetic variants involved in human myopia and refractive control are yet to be discovered. It is also probable that variants in several genes interact with one-another, as well as with environmental factors, to mediate ocular growth and produce the distributions of refraction observed in human populations. To our knowledge, gene-gene and gene-environment statistical interactions have not been systematically assessed in genetic association studies of refractive phenotypes.

Many genes found to be associated with human refractive error can be clustered into common biological networks. The largest set of these genes is involved in connective tissue growth and extracellular matrix reorganization. This group includes genes that encode matrix metalloproteinases (MMP1, MMP2, MMP3, MMP9), growth factors and growth factor receptors (HGF, TGFB1, TGFB2, MET), collagens (COL1A1, COL2A1), and proteoglycans (LUM). More recently, two studies have provided evidence for mitochondrial-mediated apoptosis as a novel mechanism for refractive error regulation (152,155). Other possible sources of refractive variation in humans have been identified in recent GWAS (153,154). One novel mechanism involves a pathway that includes Ras protein-specific guanine nucleotide-releasing factor 1 (RASGRF1)(153) and muscarinic acetylcholine receptor genes (CHRM1) (163); another implicates a role for genetic modifiers of rod-mediated visual signal transmission (154). These biological mechanisms will require external validation from experimental studies, but offer solid frameworks on which to build more comprehensive models for refractive regulation in humans.

Genomewide association studies that are currently under way will help discover new variants implicated in refractive errors, clarify the relationships between known myopia susceptibility variants, and offer greater insight into the complex mechanisms underlying refractive development. Ongoing international consortia will provide the large sample sizes required to detect rare causative polymorphisms of small effect as well as gene-gene interactions. Other promising avenues for genomic research into refractive errors include pathway and gene-set enrichment analysis approaches, the study of ocular anatomical components (such as axial length and eye shape) related to refractive error, and longitudinal analyses of individual refractive changes over time. Developing the full picture of the epidemiology of refractive error in human populations, however, will necessitate that both environmental and genetic risk factors be accounted for in future genetic epidemiological studies.

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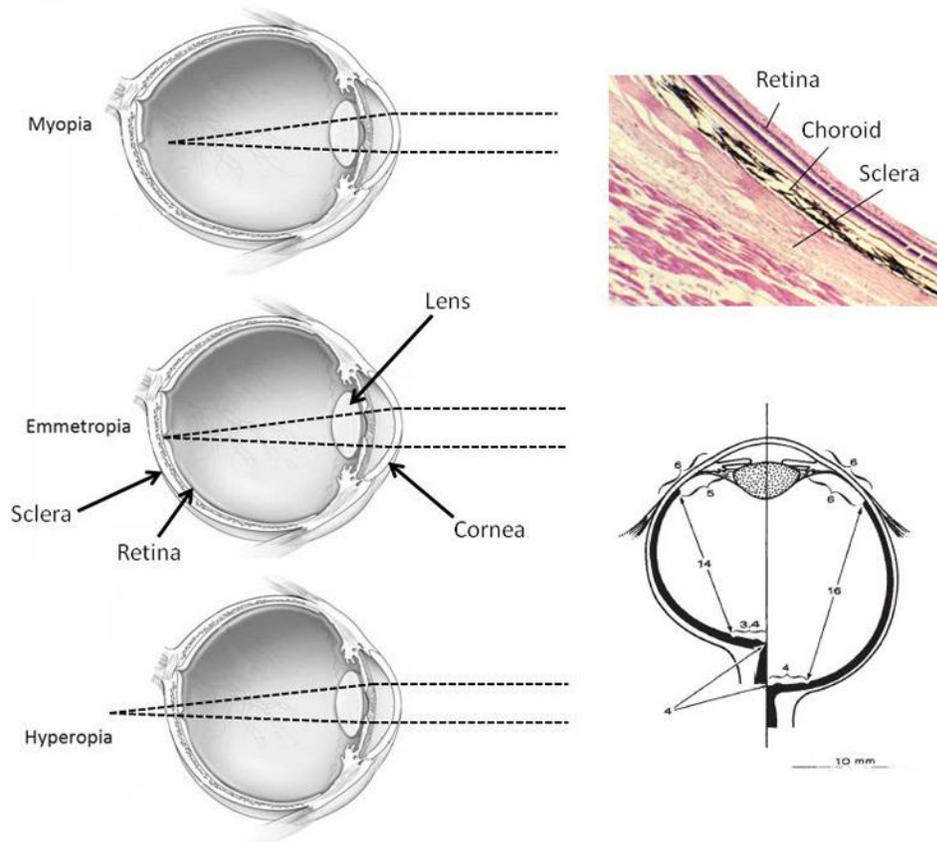


Figure 1.

The anatomical basis of refractive errors.

LEFT: Myopia or nearsightedness (top left): parallel light rays from distant objects (dashed lines) come to focus in front of the retina, causing blurred distance vision. Emmetropia or “normal” vision (middle left): incident light from distant objects are focused on the retina. Hyperopia or farsightedness (bottom left): images of distant objects are focused behind the retinal plane in an unaccommodating eye. Illustrations modified from: the National Eye Institute, National Institutes of Health (not copyrighted).

TOP RIGHT: Histological section of the posterior eye. The retina is a neurosensory tissue that detects contrast, processes the signal locally through various spatial and temporal filters, and sends the pre-processed visual signals to the visual cortex via the retinal ganglion cells. When the retina is exposed to visual signal degradation during early ocular development, it detects contrast deterioration and releases neurotransmitters to signal eye growth. These signals pass through the retinal pigmented epithelium and the vascular choroid to reach the fibrous sclera which responds with scleral tissue remodeling and axial eye growth.

BOTTOM RIGHT: Diagram illustrating the effects of form deprivation through neonatal lid fusion on various eye dimensions in rhesus monkey. The temporal halves of the eyes are juxtaposed. From Wiesel and Raviola (1977)(18), figure 2.

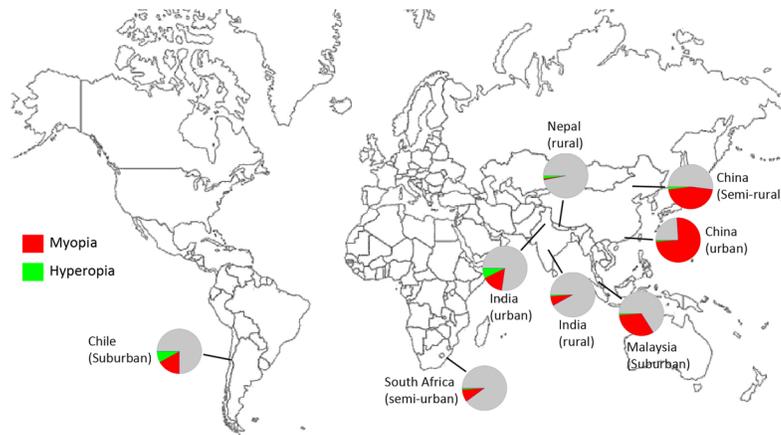


Figure 2.

Prevalence of refractive errors among 15 year-olds in the Refractive Errors Study in Children (RESC). Red shows prevalence of myopia (spherical equivalent refraction ≤ -0.5 D in both eyes); green shows prevalence of hyperopia (spherical equivalent refraction $\geq +2.50$ D in both eyes); grey shows prevalence of clinical emmetropia.

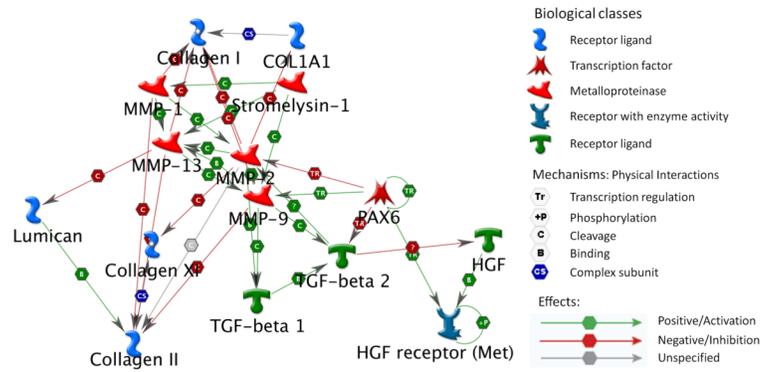


Figure 3.

First-order biological interaction network for refraction-associated genes in table 2. Genes that do not interact directly with other gene products in the network are omitted. Official gene symbol, gene names and (alternative names): COL1A1=collagen, type I, alpha 1; COL2A1= collagen, type II, alpha 1; COL11A1=collagen, type XI, alpha 1; HGF= hepatocyte growth factor (hepapoietin A; scatter factor); MET= met proto-oncogene (hepatocyte growth factor receptor); MMP1=matrix metalloproteinase 1 (interstitial collagenase); MMP2=matrix metalloproteinase 2 (gelatinase A); MMP3=matrix metalloproteinase 3 (stromelysin 1, progelatinase); MMP9=matrix metalloproteinase 9 (gelatinase B, 92kDa gelatinase, 92kDa type IV collagenase); MMP13= matrix metalloproteinase 13 (collagenase 3); LUM=lumican; PAX6= paired box 6; TGFB1= transforming growth factor, beta 1; TGFB2= transforming growth factor, beta 2.

Table 1

Summary of evidence supporting environmental and genetics influences on refractive error.

| | Examples | Evidence supporting | | | Selected references |
|---|--|---------------------|-------|--|---|
| | | Environment | Genes | Comments | |
| <i>Animal Studies</i> | | | | | |
| Form-deprivation myopia | Form deprivation through eyelid suturing or opaque lenses causes unconstrained eye growth and myopia in vertebrate models. | ++ | | Experimental form-deprivation and lens-induced refractive error studies are generally conducted in early stages of development. Results may not be applicable to adolescent and mature animals. | Wiesel and Raviola (1977)(18); Sherman et al (1977)(16); Wallman et al. (1978) (17) |
| Optical defocus-induced refractive errors | Exposure to optical defocus via plus-or minus-powered lenses causes compensatory changes in eye growth and refractive state in animal models. | ++ | | The process of emmetropization is rapid and robust during early eye development. The active emmetropization model may not be applicable to older animals. | Irving et al. (1992)(24); Smith et al. (1994)(23); Graham and Judge (1999) (22) |
| Knock-out models and QTL mapping in breeding experiments | Knockout and breeding experiments in mouse and chickens have identified genes involved in eye size and refractive regulation. | + | ++ | Few relevant knock-out animal models for refractive development exist. Visual stimuli may interact with genes in refractive control. | Zhou et al. (1999)(175); Chakravarti et al.(2003)(176); Schippert et al. (2007) (177); Chen et al (2010)(178) |
| <i>Observational studies</i> | | | | | |
| Form deprivation during infancy | Children suffering from conditions that cause a blurring of vision during the neonatal period often develop axial myopia. | ++ | | Form deprivation during infancy causes axial myopia in humans and animal models. Different mechanisms may be involved in juvenile- and adult-onset refractive errors. | Rabin et al. (1981)(19); Hoyt et al (1981) (20); Meyer et al. (1999)(21); |
| Early ocular development in infants and children | Distribution of refractive errors during infancy and early childhood follows a pattern consistent with a visually-guided feedback mechanism found in animal studies. | ++ | | Early refractive development (i.e., emmetropization) mechanisms may not be related to refractive errors developed later in life. Parental refractive status is associated with eye length in children. | Cook and Glasscock (1951)(34); Sorsby et al. (1961)(38); Larsen (1971)(36); Saunders (1995)(35); Fledelius and Cristensen (1996)(37); Mutti et al. (2005)(40) |
| Refractive development during childhood and adolescence | Prevalence of myopia increases sharply during school years through early adulthood. | ++ | + | Risk of myopia during school years is affected by environmental exposures. Refractive state in early childhood is predictive of future myopia development. | RESC studies (2000–2005)(48,55–61); Morgan and Rose (review; 2005)(42) |
| Refractive development during adulthood | “Hyperopic shift” occurs from age 40 to 60+; the prevalence of myopia decreases steadily between the 5th and 7th decades of life. | + | + | Few longitudinal studies are available in older age groups. Cross-sectional studies may be subject to confounding by cohort effects. Heritability estimates are high in older siblings. | Lee et al. (2002)(51); Guzowski et al. (2003)(52); Wu et al. (2003)(53) |
| <i>Ethnic, geographic, sex and temporal effects on refractive error</i> | | | | | |
| Ethnic differences | Individuals of Chinese and East Asian descent consistently show higher rates of myopia than non-Asians. | + | + | Possible confounding between ethnicity and culturally-specific environmental factors. | RESC studies (2000–2005)(5,55–60); Wu et al. (2001)(4); Kleinstein et al. (2003); Lam et al. (2004)(179); Rudnicka et al. (2010)(69) |

| | Examples | Evidence supporting | | | Selected references |
|--|---|---------------------|-------|--|---|
| | | Environment | Genes | Comments | |
| Geographic differences | Ethnicity-matched groups have varying rates of refractive errors depending on location of residence. | ++ | | | RESC studies (2000–2005)(5,56–58); Morgan and Rose (review; 2005)(42); Saw et al., (2006)(66) |
| Sex differences | No consistent pattern of sex differences in refractive errors across populations. Orthodox Jewish males have higher prevalence of myopia than females. X-linked forms of syndromic myopia have been identified. | + | + | Sex differences in refractive error likely due to differences in relevant environmental exposures. Familial X-linked myopia is rare and the result of a primary retinal abnormalities. | Zylberman et al. (1993)(71); Bartisocas and Kastrandias (1981)(126); Schwartz et al. (1990)(120); |
| Cohort effects and secular trends | Increase in the prevalence of myopia in some populations within the last few decades. | ++ | | Secular trends have not been universally observed across populations. Differences in data acquisition methods limit comparability with older studies. | Matsumura and Hirai (1999)(77); Lin et al. (2004)(3); Morgan and Rose (review; 2005)(42); Bar Dayan (2005)(78); Vitale et al (2009) |
| <i>Environmental and behavioral risk factors</i> | | | | | |
| Education | Higher educational attainment is associated with a greater risk of myopia and myopia progression. | ++ | | Education level is highly correlated with SES, reading/near work, measures of intelligence. | Sperduto (1983)(81); Au Eong (1993)(82); Wang (1994)(83); Katz (1997)(84); Shimizu (2003)(85); Wensor (1999)(86) |
| Socio-economic status | Higher SES is associated with greater risk of myopia. | ++ | | SES is associated with many environmental factors thought to contribute to differential risk of myopia. | Wong (2002)(80); |
| Reading/near work/studying habits | Increased reading and near work during childhood and early adulthood increase risk of myopia. | ++ | | Estimates of the relationship between exposure to near work and myopia are generally low. Measurement of near work exposure is difficult and prone to bias in retrospective studies. | Pärssinen (1989)(94); Zylberman (1993)(71,180); Kinge (2000); Saw (2002)(181); Mutti (2002)(91) |
| “Intelligence” | Positive correlation between IQ and myopia. | + | + | Possible confounding of education, school performance and reading with measures of intelligence. | Grosvenor (1970)(182); Rosner (1987)(183); Cohn (1988)(184); Teasdale (1988)(185); Saw (2006)(186) |
| Urbanization | Higher prevalence of myopia in urban versus rural areas | ++ | | Urbanization is associated with many environmental factors thought to contribute to differential risk of myopia. | Garner (1999)(187); Saw (2001)(62); Zhao (2000)(58); Zhan (2000)(188); Dandona (2002)(57); Murthy (2002)(56); He (2007)(189); Zhang (2010)(190) |
| Outdoor activity | Increased outdoor activity and participation in sports decreases the risk of myopia. | ++ | | The protective effect of outdoor activity on the risk of myopia may be limited to genetically susceptible individuals. | Mutti (2002)(91); Jones (2007)(95); Rose (2008)(96); Dirani (2009)(97); |
| Occupation | High prevalence and progression rates of myopia among occupations with high visual demand. | ++ | | | Tokoro (1988)(89); Simonsen (1994)(88); McBrien (1997)(87) |
| <i>Genetic studies</i> | | | | | |

| | Examples | Evidence supporting | | | Selected references |
|---|---|---------------------|-------|--|--|
| | | Environment | Genes | Comments | |
| Syndromic refractive errors | Several ocular or systemic syndromes with known genetic causes include myopia as a characteristic feature. | | ++ | Mapped genetic syndromes suggest mechanisms of refractive control. Genes responsible for syndromic myopia may not play significant roles in non-syndromic refractive errors. | Stickler (1965)(127); Wenstrup (1989) (191); Schwartz (1990)(120); Westling (1998)(192); |
| Effect of parental refractive status | Number of myopic parents is associated with eye size and risk of myopia in children. | | ++ | Relationship may be confounded with unmeasured shared environmental factors between parents and children. | Zadnik (1994)(110); Pacella (1999) (193); Saw (2006)(186); Jones (2007) (95); |
| Heritability and aggregation studies | Heritability and familial aggregation estimates for ocular refraction are consistently high across populations. | | ++ | Heritability estimates may be inflated due to unaccounted-for environmental correlations within families. | Teikari (1991)(101); Hammond (2001) (98); Wojciechowski (2005)(102); Peet (2007)(103) |
| Genetic linkage studies | More than 17 loci for human refractive phenotypes have been mapped | | ++ | Most linkage studies have been conducted for high myopia in highly-aggregated families. Number of loci suggests high genetic heterogeneity. | Tang (2008, review)(194), Wojciechowski (2009) |
| Segregation analyses | Segregation analyses of population-based samples support non-Mendelian, polygenic or shared environmental etiologies for refractive errors. | + | + | Few segregation analyses have been carried out. Segregation models are unreliable in the modeling of complex traits. | Ashton (1985)(115); Klein et al. (2005) (114) |
| Genetic association studies | Genetic variants in more than 25 genes have been associated with refraction phenotypes. | | ++ | Most association studies have been conducted for high or extreme myopia. Number of genes involved suggests high genetic heterogeneity and/or polygenic effects. Common biological pathways may be involved in many refractive error. Relative paucity of GWAS studies. | See table 2 |

Table 2

Studies of refraction phenotypes reporting positive association results.

| Candidate gene or candidate region studies | | | | | | | |
|--|------|-------------------|-------------------------|----------------------------------|------------------------|--------------------------------------|--|
| Study 1st author | Year | Geographic Region | Ethnicity | Phenotype | Gene symbol | Linkage Locus* Location | Associated marker(s) |
| Lam (137) | 2003 | Hong Kong | Chinese | High Myopia | TGIF1 | MYP2 18p11.31 | Codon 3 657(T->G) |
| Han (140) | 2006 | China | Han Chinese | High Myopia | HGF | --- | rs3735520 |
| Lin (135) | 2006 | Taiwan | Chinese | High Myopia | TGFB1 | --- | Codon 10 |
| Wang (148) | 2006 | Taiwan | Chinese | High myopia | LUM | MYP3 12q21-23 | rs3759223 |
| Mutti (117) | 2007 | US | Various (62% Caucasian) | Myopia | COL2A1 | STL1 | rs1635529 |
| Tang (195) | 2007 | Hong Kong | Chinese | High Myopia | MYOC | --- | rs235858, rs2421853 |
| Inamori (196) | 2007 | Japan | Japanese | High Myopia | COL1A1 | --- | rs2075555, rs2269336 |
| Andrew (152) | 2008 | UK | Caucasian | Distribution tails of refraction | MFN1 PSARL SOX2T | MYP8 3q26 3q27.1 3q26.3-q27 | Multimarker LDU mapping |
| Lin (163) | 2009 | Taiwan | Han Chinese | High Myopia | CHRM1 | --- | rs544978, rs542269 |
| Lin (136) | 2009 | Taiwan | Han Chinese | High Myopia | TGFB2 | --- | rs7550232 |
| Ng (197) | 2009 | Hong Kong | Han Chinese | High Myopia | PAX6 | MYP7 11p13 | Dinucleotide repeats in promoter region |
| Yanovitch (139) | 2009 | US | Caucasian | Mild/Moderate Myopia | HGF | --- | rs3735520 |
| Han (198) | 2009 | Hong Kong | Han Chinese | High Myopia | PAX6 | MYP7 11p13 | rs3026393 |
| Vatavuk (199) | 2009 | Croatia | Caucasian | High Myopia | MYOC | --- | rs2421853 |
| Zha (200) | 2009 | Hong Kong | Chinese | High Myopia | TGFB1 | --- | rs1800470, rs4803455 |
| Metlapally (118) | 2009 | US & Wales | Caucasian | High Myopia | COL2A1 | STL1 | rs1635529 |
| Khor (141) | 2009 | Singapore | Chinese | Myopia/myopia progression | CMET | --- | rs2073560 |
| Chen (146) | 2009 | Taiwan | Han Chinese | High Myopia | LUM | MYP3 12q21-23 | rs3759223-rs3741834 haplotype block |
| Hall (144) | 2009 | UK | Caucasian | Myopia | MMP3 MMP9 | --- | 11q22.3 20q11.2-q13.1 MMP-3 gene 1612 insA MMP-9 gene exon 6 Arg->Gln |
| Zayats (201) | 2009 | US & Wales | Caucasian | High Myopia | MYOC | --- | rs1684720, NGA17 (microsatellite) |
| Liu (202) | 2009 | Taiwan | N/A | High Myopia | BMP2K | MYP9 4q12 | rs2288255 |

| Candidate gene or candidate region studies | | | | | | | |
|--|------|---------------------------------------|-----------|---|-------------------|------------------------------|--|
| Study 1st author | Year | Geographic Region | Ethnicity | Phenotype | Gene symbol | Linkage Locus* Location | Associated marker(s) |
| Nishizaki (203) | 2009 | Japan | Japanese | High Myopia | UMODL1 | --- 21q22.3 | rs2839471 |
| Veerappan (138) | 2010 | Australia | | Low/moderate myopia Hyperopia | HGF HGF | --- 7q21.1 | rs1743, rs4731402, rs12536657, rs10272030, rs9642131 rs12536657, rs5745718 |
| Mettapally (143) | 2010 | US, UK, Denmark, Australia, France | Caucasian | High Myopia, Myopia | IGF1 | MYP3 12q21-23 12q23.2 | rs6214 |
| Wojciechowski (145) | 2010 | US | Amish | Ocular refraction | MMP1 MMP2 | --- 11q22.3 --- 16q13-q21 | rs1939008 rs9928731 |
| Lin (147) | 2010 | Taiwan | Chinese | High Myopia | LUM | MYP3 12q21-23 12q21.3-22 | SNP haplotypes within promoter region |
| Khor (142) | 2010 | Singapore | Chinese | Myopia/High Myopia | TGFB1 | --- 19q13.1 | rs4803455 |
| Genomewide Association Studies (GWAS) | | | | | | | |
| Study 1st author | Year | Geographic Region | Ethnicity | Phenotype | Gene symbol | Proximal Locus Location | Associated marker(s) |
| Nakanishi (155) | 2009 | Japan | Japanese | Pathological Myopia | BLID LOC399959 | --- 11q24.1 | rs577948 |
| Hysi (153), ENREF_134, ENREF_117 | 2010 | U.K., Netherlands, Australia | Caucasian | Ocular refraction | RASGRF1 | --- 15q25.1 | rs939658, rs8027411 |
| Solouki (154) | 2010 | Netherlands U.K. (replication) | Caucasian | Ocular refraction Myopia and Hyperopia | GJD2 ACTC1 | --- 15q14 | rs634990 |

* Linkage locus indicated by gene names and cytogenetic location of nearby linkage loci for refractive errors or myopia. STL1–Stickler Syndrome, Type 1.