Clinical science

Lower indoor spatial frequency increases the risk of myopia in children

Dan-Lin Li ,[1] Xing-Xuan Dong ,[1] Jin-Liu-Xing Yang ,[1,2] Carla Lanca,[3] Andrzej Grzybowski ,[4] Chen-Wei Pan [1]

► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/bjo-2024-325888).

[1]School of Public Health, Suzhou Medical College of Soochow University, Suzhou, China
[2]Shanghai Eye Diseases Prevention & Treatment Center, Shanghai Eye Hospital, School of Medicine, Tongji University, Shanghai, China
[3]Escola Superior de Tecnologia da Saúde de Lisboa (ESTeSL), Instituto Politécnico de Lisboa, Lisboa, Portugal; Comprehensive Health Research Center (CHRC), Escola Nacional de Saúde Pública, Universidade Nova de Lisboa, Lisboa, Portugal
[4]Institute for Research in Ophthalmology, Foundation for Ophthalmology Development, Poznan, Poland

Correspondence to
Prof. Chen-Wei Pan; pcwonly@gmail.com

Received 24 May 2024
Accepted 27 July 2024

ABSTRACT

Background/aims Animal models have shown that the absence of high-frequency visual information can precipitate the onset of myopia, but this relationship remains unclear in humans. This study aims to explore the association between the spatial frequency content of the visual environment and myopia in children.

Methods Images from the rooms of children and their frequently visited outdoor areas were taken by their parents and collected by the researcher through questionnaires. The spatial frequency was quantified using Matlab. Cycloplegic refraction was used to measure the spherical equivalent (SE), and IOL Master was used to measure axial length (AL) and corneal radius (CR). AL/CR ratio was calculated.

Results The study included 566 children with an average age of (8.04±1.47) years, of which 270 were girls (47.7%), and the average SE was (0.70±1.21) D. Image analysis revealed that indoor spatial frequency slope was lower than that of the outdoor environment (−1.43±0.18 vs −1.11±0.23, p<0.001). There were 79 myopic individuals (14.0%). Images from indoor content of myopic children had a lower spatial frequency slope than non-myopic children (−1.47±0.16 vs 1.43±0.18, p=0.03) while there was no significant difference in outdoor spatial frequency slope. Regression analysis indicated that the indoor spatial frequency slope was positively associated with SE value (β=0.60, p=0.02) and inversely related to myopia (OR=0.24, p<0.05).

Conclusion The spatial frequency of the outdoor environment is significantly higher than that of the indoor environment. Indoor spatial frequency is related to children's refractive status, with lower indoor spatial frequency being associated with a higher degree of myopia.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The visual environment is closely associated with the normal refractive development. Animal models have shown that the absence of high-frequency visual information can lead to the onset of myopia. However, there is little evidence of the association between the spatial frequency content of the visual environment and myopia in children.

WHAT THIS STUDY ADDS

⇒ Our study based on a population found that the spatial frequency slope of indoor environments was significantly lower than that of outdoors. Less high spatial frequency content indoors was associated with myopia among children.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ The findings suggest that if high-frequency content can be increased indoors to replicate the spatial frequency content of the outdoor environment, the risk of myopia may be reduced.

INTRODUCTION

Myopia has become a global public health issue, with persistently high prevalence rates, particularly in East and Southeast Asia.[1] Myopia is caused by a complex interplay between genetic and environmental factors, and its prevention and control currently focus mostly on environmental and behavioural interventions.[2 3] Randomised controlled intervention trials have shown that outdoor time is an effective preventive measure for myopia, with 2 hours per day outdoors being generally recommended.[4–6] However, due to educational and homework pressures, as well as the widespread use of electronic devices, children and adolescents often engage in less than the recommended 2 hours of outdoor activity per day.[7–9] The average daily outdoor time for 9 years in Singapore is reported to be about 100 min, while in China, school-age children spend about 91–112 min.[4 7 8 10] It has been found that adherence to spending adequate time outdoors is low. Therefore, simply increasing outdoor time has limited effects on myopia prevention and control.[11] It is necessary to explore the key elements that cause differences in myopia risk between outdoor and indoor environments among children and adolescents.

Features of the visual environmental exposures are closely related to the occurrence of myopia.[12] Normal refractive development requires visual stimulation from the environment, and abnormal visual input can disrupt this process, leading to myopia.[13 14] Based on the chromatic and luminance characteristics of the visual environment, previous studies have found that lower light intensity and shorter wavelength are significant factors affecting the onset and progression of myopia.[15] In recent years, researchers found that spatial frequency content differences between indoor and outdoor

Check for updates

To cite: Li D-L, Dong X-X, Yang J-L-X, *et al*. *Br J Ophthalmol* Epub ahead of print: [*please include* Day Month Year]. doi:10.1136/bjo-2024-325888

environments may play a role in the occurrence and development of myopia.[16]

Compared with the natural environment, the indoor environment exhibits similar spatial frequency characteristics to animal models that induce form deprivation myopia, specifically, a lack of higher spatial frequencies.[12] There is a significant structural difference between natural and man-made environments, as indoor structures lack common attributes present in natural scenes. High-frequency visual information may be crucial for maintaining normal refractive development, which is disrupted, leading to excessive development of axial length (AL) triggering myopia.[14] In chicks and guinea pigs, a scarcity of high-frequency visual information has been found to result in abnormal refractive development and myopia.[14 17] Nevertheless, the association between spatial frequency of visual information and myopia is mostly limited to animal models, with very few studies conducted in populations. If the lack of higher spatial frequency content in indoor scenes contributes to the development of myopia in humans, it would make practical sense to increase indoor high-frequency information by reproducing the spatial frequency of the outdoor environment to reduce the risk myopia. Previously, Yi *et al* set up a classroom environment resembling an outdoor scene but did not specifically evaluate the spatial frequency and its association with myopia.[18]

Thus, the aim of the present study was to explore the association between the spatial frequency content of the visual environment and myopia in children.

METHODS

Study population

This study was conducted at two primary schools and one kindergarten in Shanghai from March 2022 to December 2022 by convenience sampling. The study enrolled students aged 5–12 years who had lived at their current address for a minimum of 6 months. The exclusion criteria were as follows: (1) the presence of organic eye diseases such as glaucoma, strabismus, etc; (2) non-cooperation during eye examinations or failure to meet the requirements for cycloplegic refraction; (3) high myopia (SE≤−6.0 D) or high hyperopia (SE≥5.0 D) in one or both eyes and (4) previous use of myopia-related interventions such as atropine, corneal reshaping lenses and red light therapy.

During the recruitment process, electronic questionnaires were distributed for completion by participants' parents or guardians for the collection of basic information and environmental images. A total of 1559 questionnaires were collected, excluding duplicates and subjects with inadequate images, leaving 1074 individuals with complete image information. Among those with complete image information, appointments were scheduled for eye examinations, and 574 individuals completed the examinations. Eight individuals were excluded postexamination for high myopia or hyperopia, leaving 566 for analysis. No statistically significant differences were found in age, sex or indoor/outdoor spatial frequency between the participants included in the study and those who did not participate in the eye examinations and were subsequently excluded.

Images collection and spatial frequency analysis

Images of the indoor and outdoor environments of the research subjects were collected through an electronic questionnaire, which was taken and filled out by their parents or guardians using their mobile phones. To ensure standardised and high-quality image capture, examples of the required images were provided in the electronic questionnaire (figure 1A). Indoor

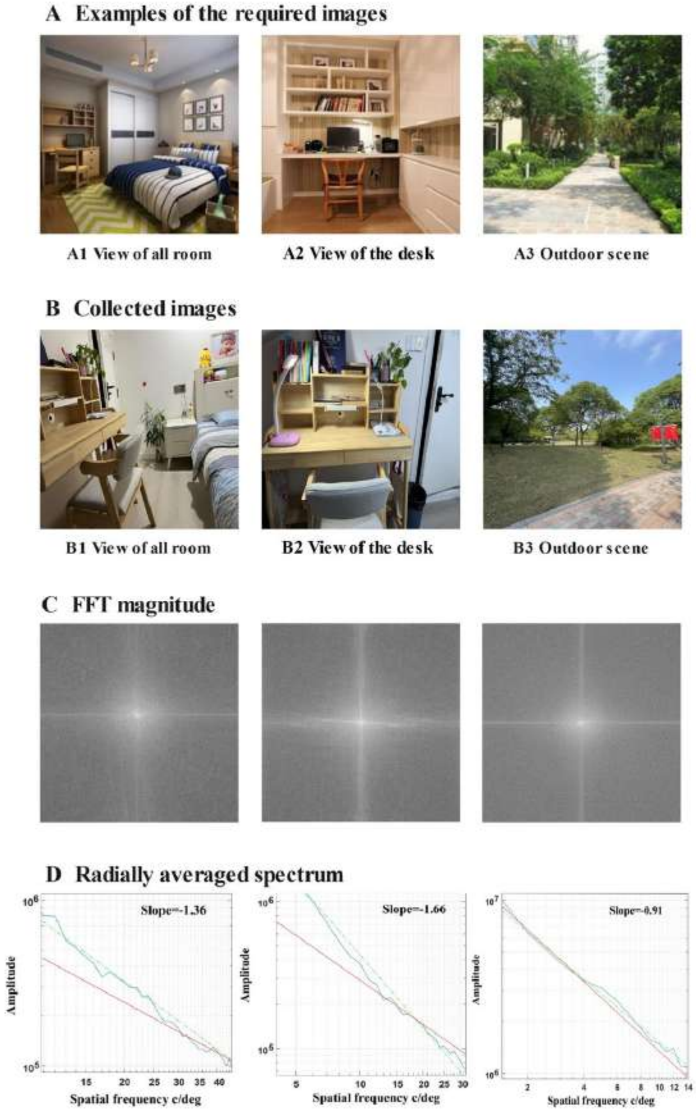

Figure 1 The diagram of the spatial frequency analysis process.

images were captured from two distinct angles including an entire room panorama and desk panorama, and a single picture was taken of the frequently used outdoor area. Instructions for collecting images to the parents were given to (1) ensure high clarity during capture; (2) try to select a time frame between 16:00 and 18:00 hours to avoid direct sunlight and minimise the impact of light intensity; (3) maintain a certain range of view during photography to avoid close-up shots; (4) try to avoid people in the images. On retrieval of the images, researchers screened and evaluated the images for inclusion. An example of the collected image is shown in figure 1B. Images that did not match the content or had a resolution of less than 1024×1024 were excluded.

Spatial frequency analysis was carried out using Matlab. The feasibility and rationality of this method have been demonstrated in previous studies.[16 19] The initial step was image preprocessing, which involved adjusting the resolution of the images to a uniform size of 1024×1024 pixels, converting them from the RGB colour system to greyscale and LMS colour space. Subsequently, a two-dimensional Fourier transformation was performed, shifting the zero-frequency point to the centre of the image and radially averaging the spectrum information in each direction (figure 1C). Finally, a logarithmic coordinate axis with a base of 10 was created for fitting linearly the amplitude and spatial frequency of each pixel, aiming to obtain the slope value of the overall spatial frequency spectrum fitting of the image (figure 1D). This slope value reflects the magnitude of the spatial frequency of the image. Previous research has shown that following these steps, the theoretical value of the spatial frequency slope for natural images is −1.0.[16 19] The lack of higher spatial frequencies leads to a stepper decline in amplitude so a smaller slope value indicates a smaller spatial frequency of the environment represented by the image.

Eye examination

After collecting the images, we confirmed that the inclusion criteria had been met. On confirmation, an appointment was scheduled for an ophthalmic examination. The examination was conducted at an ophthalmic hospital in Shanghai by an optometrist. Initially, the IOL Master (V.5.02, Carl Zeiss, Jena, Germany) was used to measure the AL and the average corneal radius (CR). Measurements were taken three times consecutively, and the average was recorded. Any discrepancy between two measurements exceeding 0.02 mm warranted a remeasurement. The ratio of AL to average CR was termed the AL/CR.

Subsequently, cycloplegic refraction was employed to obtain the refractive information of the subjects. During this process, 1% cyclopentolate hydrochloride was administered as the mydriatic agent. First, one drop of proparacaine hydrochloride is applied, followed by one drop of cyclopentolate hydrochloride 15 s later, and then another drop of cyclopentolate hydrochloride is applied at 5 min. After each application, students were instructed to gently press the medial canthus for several seconds and to assume a reclined head position. The final drop was applied at 30 min intervals, and pupil dilation and light reflex were examined. Cycloplegia was defined by the disappearance of the pupillary reflex. If ciliary paralysis has not been achieved, a third drop is administered, and the condition is re-evaluated after an additional 15 min. After confirming cycloplegia, an automatic desktop refractometer (KR-8900; Topcon, Japan) was used for refraction. Measurements were taken for the right eye, followed by the left eye, with each eye undergoing three repeated measurements, and the average was calculated. If there was a difference of more than 0.50 D between any two measurements, the process was repeated. The spherical equivalent (SE) was calculated as the spherical dioptre+0.5×the cylindrical dioptre. Myopia was defined as the SE value less than or equal to −0.50 D.

Covariate information

Basic demographic information of the participants was collected through questionnaires, which included the name, sex (boy or girl), height, weight and the duration of residence in the current location (less than 3 years, 3 to 5 years, more than 5 years). The brightness and contrast values were calculated through the images. Brightness was measured in grey-scale value (G), ranging from 0 to 255, with higher values indicating lighter colours. Contrast represented the degree of grayscale variation in an image, and it was unitless. A higher contrast value signified a greater degree of variation between light and dark areas in the image.

Quality control

To ensure the quality of the study, researchers first created the electronic link for the questionnaire and filled it out multiple times to ensure its accuracy. Before filling out the questionnaire, investigators provided a detailed explanation of the survey's purpose and the precautions for taking images. It was mandatory for participants to fully complete the questionnaire before submission. After submission, researchers excluded questionnaires with obvious errors and deleted images that did not meet the standard based on the inclusion and exclusion criteria for image assessment. Ophthalmic examinations were performed by professional optometrists at a tertiary hospital. During the measurement process, both optometric checks and AL assessments were conducted three times, with the average value being recorded. If the error exceeded the expected value, the measurement was repeated.

Table 1 Characteristics of refractive parameters and differences across various refractive statuses in the participants

Variables	Total	Myopia (79, 14.0%)	Non-myopia (487, 86.0%)	P value
Age (year)	8.04±1.47	8.90±0.94	7.90±1.50	<0.001
Height (cm)	121.21±10.32	127.01±6.90	120.26±10.48	<0.001
Weight (kg)	25.00±6.76	28.10±6.78	24.50±6.62	<0.001
SD (D)	1.01±1.23	−1.15±0.84	1.36±0.88	<0.001
CD (D)	−0.61±0.54	−0.70±0.59	−0.60±0.53	0.14
SE (D)	0.70±1.21	−1.50±0.86	1.06±0.82	<0.001
AL (mm)	22.84±0.91	23.92±0.77	22.67±0.80	<0.001
CR (mm)	7.83±0.28	7.84±0.28	7.82±0.27	0.55
AL/CR	2.92±0.09	3.05±0.09	2.90±0.08	<0.001

AL, axial length; CD, cylindrical dioptre; CR, corneal radius; SD, spherical dioptre; SE, spherical equivalent.

Statistical analysis

Excel was used to organise questionnaire data. The spatial spectral slope, brightness and contrast value of the images were calculated using Matlab R2021a. Additionally, there was a high correlation between the SE, AL, CR and AL/CR of the left and right eyes, with correlation coefficients exceeding 0.9 (all $p<0.001$). Subsequent analyses were conducted using data from the right eye. Independent samples t-tests were used to compare spatial frequency distributions for different refractive states. AL, CR, AL/CR, SE and myopia were used as outcomes to analyse the relationship between spatial frequency and them. All analyses of the study were conducted in SPSS V.23.0. A $p<0.05$ was considered statistically significant in this study.

RESULTS

A total of 566 participants were included in the study, with an average age of (8.04±1.47) years, comprising 296 boys (52.3%) and 270 girls (47.7%). The refractive parameters and differences across various refractive statuses are detailed in table 1. The mean values for sphere, cylinder and SE were 1.01 D, −0.61 D and 0.70 D, respectively. For AL, CR and AL/CR ratio, the mean values were 22.84 mm, 7.83 mm and 2.92, respectively. Myopic individuals exhibited significantly higher spherical dioptres, longer ALs, flatter CRs and higher AL/CR ratios compared with those without myopia (all $p<0.05$).

Figure 2 illustrates the distribution of spatial spectral slope for indoor and outdoor environments. The spatial spectral slope of the indoor environment followed a normal distribution (skewness=0.09, kurtosis=−0.22, P for K-S test=0.20), with an average of (−1.43±0.18), ranging from a maximum of −0.95 to a minimum of −1.95. For the outdoor environment, the spatial spectral slope ranged from −1.92 to −0.63, with an average of −1.11±0.23. The distributions were skewed (kurtosis=−0.14, skewness=−0.43, P for K-S test<0.001). The

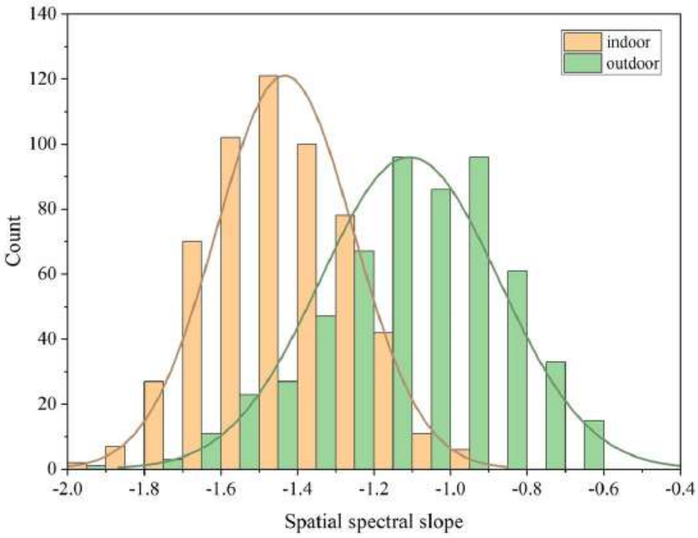

Figure 2 Distribution of indoor and outdoor spatial spectral slope in the sample.

difference in spatial spectral slopes between indoor and outdoor environments was significant (p<0.001).

There were 79 myopic individuals, with a myopia prevalence of 14.0%. Figure 3 shows the differences in indoor and outdoor spatial spectral slopes among different refractive groups. Images taken from rooms of myopic individuals had significant (p=0.03) lower indoor spatial spectral slope (−1.47±0.16) compared with non-myopic individuals (−1.43±0.18). However, there was no significant difference in images from outdoor spatial spectral slopes between myopic and non-myopic individuals (−1.12±0.27 vs −1.10±0.23, p>0.05).

Table 2 shows the relationships between spatial spectral slopes in indoor and outdoor environments with SE and myopia. After adjusting for age, sex, height, weight, residence time, indoor brightness and indoor contrast, an increase of one unit in indoor spectral slope was associated with a 0.6 D increase in SE (p=0.022) and a 76.0% reduction in the risk of myopia (p=0.049). Regarding the relationship of outdoor spatial spectral slope with SE and myopia, neither the crude nor the multivariable models suggested an association between outdoor spatial spectral slope and SE or myopia (both p>0.05).

The regression models of the association between indoor and outdoor spatial spectral slopes and refractive parameters are presented in online supplemental table 1. In the multivariable models adjusted for the confounding factors, the β (95%CI) values for AL, CR and AL/CR were −0.18 (−0.52 to 0.16), 0.02 (−0.10 to 0.14), and −0.03 (−0.07 to 0.01), respectively (all p>0.05). No significant association was observed between outdoor spatial spectral slopes and AL, CR or AL/CR (all p>0.05).

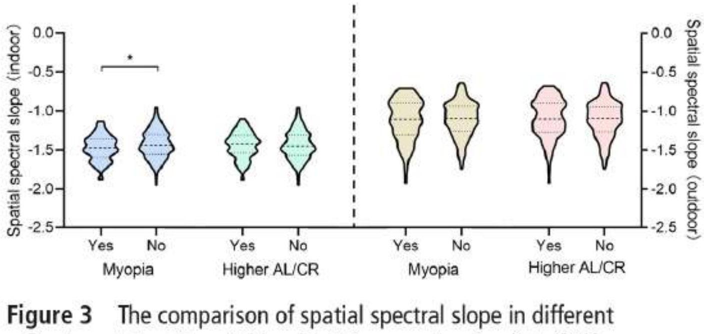

Figure 3 The comparison of spatial spectral slope in different refractive status. AL, axial length; CR, corneal radius. * P<0.05.

DISCUSSION

Our study quantitatively assessed the environmental spatial frequency and found an association between refractive parameters after cycloplegic refraction, controlling for the effects of brightness and contrast. We found that the spatial frequency slope of indoor environments was significantly lower than that of outdoor environments. Less high spatial frequency content indoors was associated with myopia. However, no significant association was found with AL, CR or AL/CR. In contrast, outdoor spatial frequency showed no significant association with myopia or refractive parameters. The results of study may suggest that if high-frequency content can be increased indoors, reproducing the spatial frequency content of the outdoor environment, myopia prevention might be possible. However, further randomised controlled studies are necessary to confirm this hypothesis.

In this study, the spatial spectral slope value was derived from the image using a series of operations such as Fourier transformation and radial averaging to quantitatively assess the spatial frequency of the environment. Previous studies have shown that, despite the diversity exhibited in images, the frequency spectra distributions of outdoor scenes are consistent.[16 19] Consistent with published findings, our results showed that indoor spaces contain fewer high-frequency components than outdoor environments.[16] Previous research has suggested that the lack of high spatial frequency components indoors could have the same effect as a 0.4 Bangerter foil in inducing myopia in animal models.[14 16] In our study, increasing high spatial frequency information indoors to those seen outdoors could potentially improve refractive status by 0.2 D and reduce the risk of myopia by approximately 24.3%. Nevertheless, it is important to note that the p value was at the threshold of statistical significance, which may limit the generalisation of the results. Further research should be conducted for different age groups and in different regions to validate the observed association. Further exploration of temporal effects is also needed. Interestingly, a significant difference was observed in the spatial frequencies of environments limited to indoors between myopic and non-myopic children. This observation can likely be attributed to the fact that spatial frequency variations are often more pronounced indoors compared with the relatively consistent levels outdoors. Additionally, even the lower spatial frequencies encountered outdoors are generally higher than those found indoors, which may further contribute to this difference. These findings suggest that indoor environments may play a crucial role in the development of myopia, and future studies should further investigate the impact of spatial frequency variations on myopia progression.

The underlying retina mechanisms involved in the effect of spatial frequency on the development of myopia are summarised in figure 4. From an optical perspective, retinal contrast sensitivity is the basis for retinal perception of spatial frequency.[20 21] Lower spatial frequency is usually accompanied by a reduction in the contrast of the visual environment, and higher spatial frequency components translate into greater contrast on the retina.[20 21] The sensitivity of the human eye to spatial frequency is inversely proportional to the contrast of the grating.[22] Based on the relationship between spatial frequency and contrast, the contrast sensitivity function of the human eye can be plotted.[23] As the spatial frequency of the visual input signal increases, the degradation of retinal image contrast due to defocus blur also

Table 2 Associations of spatial spectral slope with SE and myopia

	SE (D)*				Myopia†			
	Crude model		Multivariable model‡		Crude model		Multivariable model‡	
Variable	β (95% CI)	P value	β (95% CI)	P value	OR (95% CI)	P value	OR (95% CI)	P value
Indoor								
Brightness (G, per 10 unit)	0.06 (0.00 to 0.11)	0.049	0.03 (−0.02 to 0.08)	0.291	0.89 (0.78 to 1.01)	0.078	0.93 (0.81 to 1.06)	0.289
Contrast (per 10 unit)	0.01 (−0.13 to 0.16)	0.846	0.01 (−0.13 to 0.14)	0.966	0.70 (0.49 to 0.99)	0.042	0.69 (0.48 to 0.99)	0.042
Spatial spectral slope (per unit)	0.66 (0.10 to 1.22)	0.021	0.60 (0.09 to 1.12)	0.022	0.25 (0.06 to 0.97)	0.046	0.24 (0.06 to 0.99)	0.049
Outdoor								
Brightness (G, per 10 unit)	0.04 (−0.02 to 0.09)	0.190	0.02 (−0.03 to 0.07)	0.478	0.90 (0.80 to 1.03)	0.904	0.92 (0.81 to 1.06)	0.923
Contrast (per 10 unit)	−0.02 (−0.15 to 0.10)	0.717	−0.04 (−0.15 to 0.08)	0.554	1.08 (0.80 to 1.45)	0.621	1.12 (0.82 to 1.53)	0.478
Spatial spectral slope (per unit)	0.33 (−0.12 to 0.78)	0.153	0.09 (−0.32 to 0.51)	0.663	0.63 (0.22 to 1.83)	0.398	0.75 (0.25 to 2.25)	0.604

*Linear regression model.
†Logistic regression model.
‡Adjusted for age, sex, height, weight and residence time group.
CI, confidence interval; OR, odds ratio; SE, spherical equivalent; β, coefficient.

increases, indicating that the eye is more sensitive to contrast changes in higher frequency signals.[24] By using mfERG measurements, Chin *et al* demonstrated that the retina responds more strongly to defocus with lower spatial frequency visual signals, suggesting that the retina, in addition to decoding defocus according to wavelength through longitudinal chromatic aberration and the visual pathway, tunes according to spatial frequency mnemonics, which is also part of the optical defocusing system.[25] Furthermore, Tran *et al* proposed that the process of emmetropisation may be coordinated to mid-spatial frequencies, as this tuning would prevent a small degree of retinal image degradation from temporary fluctuations in higher-order optical aberrations.[26] The absence of mid-frequency to high-frequency visual information can reduce contrast sensitivity, which becomes particularly critical at high contrasts, and such a reduction can contribute to the development of myopia when combined with low-frequency information and low contrast.[22 23]

From the neurophysiological perspective, the influence of visual environment spatial frequency on myopia may be related to the processing of visual information and the transmission of neural signals.[27 28] Light wavelength and intensity are known to affect myopia by influencing retinal dopamine secretion.[29] In chicks, both spatial information deprivation and reduced luminance decrease retinal dopamine secretion[15 21 29 30] Thus, spatial frequency regulation of eye growth may be related to retinal dopamine in humans. It has been shown that dopamine D2 receptors modulate the spatial frequency selectivity of neurons in the visual system, and the deletion of the D2 receptor gene in mice increases the sensitivity of the visual cortex V1 to spatial frequency.[29] When dopamine D1 receptor activity decreases, horizontal cell coupling increases, lowering the spatial frequency threshold.[31] In this process, spatial frequency also leads to varying activation levels of the ON-OFF visual pathways, as animal models show that OFF pathway activation is five times more pronounced at low spatial frequencies compared with ON pathway activation.[32–34] During signalling activation, the visual gap protein has been noted to be an important link in the signalling process from optic rod cell output to ON ganglion cells, which suggested that spatial frequency signalling may play a role in myopia formation by affecting retinal optic rod signalling pathways.[35 36]

In our study, indoor spatial frequency was significantly correlated with SE, but not with AL, CR or AL/CR. To our knowledge, while there is a significant correlation between SE

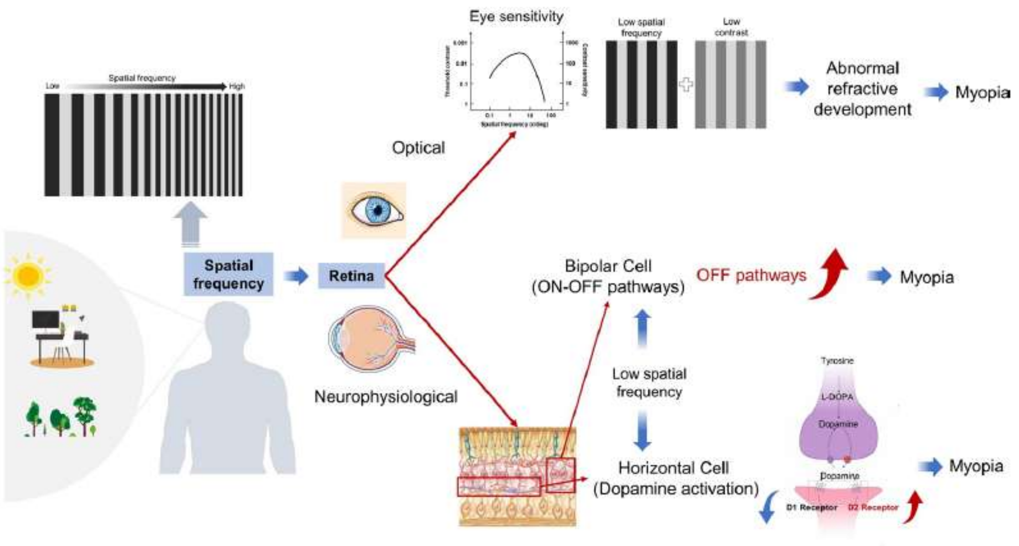

Figure 4 The underlying retina mechanisms involved in the effect of spatial frequency on the development of myopia. (Eye sensitivity[39] dopamine synthesis and release[31]).

and AL, CR and AL/CR, higher interindividual variability has been observed in SE compared with the less variable AL and AL/CR.[37] Additionally, while elongation of the AL can alter the eye's shape, changes in CR and lens refraction can compensate for the increased AL.[38] Furthermore, in our study, SE measurements were obtained following cycloplegia, which is considered the gold standard for assessing myopia.

In summary, our study provided population-based data on the relationship between spatial frequency and myopia. Despite being a cross-sectional study, the home environment represents a long-term and stable setting. The relationship between environment and myopia is well known and it seems unlikely that being myopic would lead to changes in the home environment. However, there are some limitations of this study to consider. First, the assessment of spatial frequency relied on the photographs provided by the parents, introducing the potential for reporting bias, similar to questionnaires. To mitigate subjectivity, we provided specific examples and conducted image screening. Second, all images were captured using a mobile phone, which limited our ability to standardise shooting parameters and calculate illuminance values. Nevertheless, the brightness and contrast of the images were extracted and controlled in the analysis. Third, in addition to the confounders already considered, some other factors that may affect myopia, such as outdoor time, were not considered in our analysis. Special attention needs to be paid to control these additional confounding factors in future studies and validations. Finally, the subjects were recruited from a single-centre, highlighting the need for future research to validate the association between spatial frequency and myopia across diverse regions and age groups.

CONCLUSION

Outdoor scenes have higher levels of high-frequency components than indoors. A significant relationship between spatial frequency and myopia was found only in the indoor environment. Lower spatial frequency in the indoor environments, with fewer high-frequency components, was associated to myopia. The findings suggested that the protective effect of outdoor activities against myopia may stem not only from the levels of illumination but also from other characteristics, such as spatial frequency. Enhancing children's home environments by increasing high-frequency components may be a new strategy to prevent myopia, although further studies are necessary to confirm our results.

Acknowledgements We are sincerely grateful to Professor Ian Morgan for his critical guidance on the article. And thanks are also due to all the participants and schools involved in the survey, as well as all the field staff.

Contributors D-LL attended the investigation, performed the statistical analyses and drafted the manuscript. X-XD revised the manuscript. J-L-XY attended the investigation and revised the manuscript. CL and AG revised the manuscript. C-WP conceptualised the question, supervised the study, revised the manuscript and provided funding for the project. C-WP is the guarantor. All authors read and approved the final manuscript.

Funding This research was supported by the National Natural Science Foundation of China (grant number 82122059).

Disclaimer The sponsor or funding organisation had no role in the design or conduct of this research.

Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants and was approved by Ethics Committee of Soochow University (Number: SUDA20221229H10). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request. The datasets generated and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

ORCID iDs
Dan-Lin Li http://orcid.org/0000-0003-0800-4308
Xing-Xuan Dong http://orcid.org/0000-0001-6791-4833
Jin-Liu-Xing Yang http://orcid.org/0000-0002-4031-7040
Andrzej Grzybowski http://orcid.org/0000-0002-3724-2391
Chen-Wei Pan http://orcid.org/0000-0003-3362-4613

REFERENCES

1 Dolgin E. The myopia boom. *Nature New Biol* 2015;519:276–8.
2 Morgan IG, Wu P-C, Ostrin LA, *et al*. IMI Risk Factors for Myopia. *Invest Ophthalmol Vis Sci* 2021;62:3.
3 Biswas S, El Kareh A, Qureshi M, *et al*. The influence of the environment and lifestyle on myopia. *J Physiol Anthropol* 2024;43:7.
4 He X, Sankaridurg P, Wang J, *et al*. Time Outdoors in Reducing Myopia: A School-Based Cluster Randomized Trial with Objective Monitoring of Outdoor Time and Light Intensity. *Ophthalmology* 2022;129:1245–54.
5 He M, Xiang F, Zeng Y, *et al*. Effect of Time Spent Outdoors at School on the Development of Myopia Among Children in China: A Randomized Clinical Trial. *JAMA* 2015;314:1142–8.
6 Wu P-C, Tsai C-L, Wu H-L, *et al*. Outdoor activity during class recess reduces myopia onset and progression in school children. *Ophthalmology* 2013;120:1080–5.
7 Yang J-L-X, Li D-L, Chen J, *et al*. Effect modification of time spent outdoors on the association between early childhood overweight and myopia: a one-year follow-up study. *J Public Health (Oxf)* 2024;46:107–15.
8 Li M, Lanca C, Tan C-S, *et al*. Association of time outdoors and patterns of light exposure with myopia in children. *Br J Ophthalmol* 2023;107:133–9.
9 Li S-M, Ran A-R, Kang M-T, *et al*. Effect of Text Messaging Parents of School-Aged Children on Outdoor Time to Control Myopia: A Randomized Clinical Trial. *JAMA Pediatr* 2022;176:1077–83.
10 Jiang D, Lin H, Li C, *et al*. Longitudinal association between myopia and parental myopia and outdoor time among students in Wenzhou: a 2.5-year longitudinal cohort study. *BMC Ophthalmol* 2021;21:11.
11 Jones-Jordan LA, Sinnott LT, Cotter SA, *et al*. Time outdoors, visual activity, and myopia progression in juvenile-onset myopes. *Invest Ophthalmol Vis Sci* 2012;53:7169–75.
12 Choi KY, Chan SS-H, Chan HH-L. The effect of spatially-related environmental risk factors in visual scenes on myopia. *Clin Exp Optom* 2022;105:353–61.
13 Rucker F. Monochromatic and white light and the regulation of eye growth. *Exp Eye Res* 2019;184:172–82.
14 Hess RF, Schmid KL, Dumoulin SO, *et al*. What image properties regulate eye growth? *Curr Biol* 2006;16:687–91.
15 Zhang P, Zhu H. Light Signaling and Myopia Development: A Review. *Ophthalmol Ther* 2022;11:939–57.
16 Flitcroft DI, Harb EN, Wildsoet CF. The Spatial Frequency Content of Urban and Indoor Environments as a Potential Risk Factor for Myopia Development. *Invest Ophthalmol Vis Sci* 2020;61:42.
17 Zhi Z, Pan M, Xie R, *et al*. The effect of temporal and spatial stimuli on the refractive status of guinea pigs following natural emmetropization. *Invest Ophthalmol Vis Sci* 2013;54:890–7.
18 Yi X, Wen L, Gong Y, *et al*. Outdoor Scene Classrooms to Arrest Myopia: Design and Baseline Characteristics. *Optom Vis Sci* 2023;100:543–9.
19 Tolhurst DJ, Tadmor Y, Chao T. Amplitude spectra of natural images. *Ophthalmic Physiol Opt* 1992;12:229–32.
20 Swiatczak B, Schaeffel F. Myopia: why the retina stops inhibiting eye growth. *Sci Rep* 2022;12:21704.
21 Feldkaemper M, Diether S, Kleine G, *et al*. Interactions of spatial and luminance information in the retina of chickens during myopia development. *Exp Eye Res* 1999;68:105–15.
22 Ye Y, Xian Y, Liu F, *et al*. Characteristics and Related Parameters of Quick Contrast Sensitivity Function in Chinese Ametropia Children. *Eye Contact Lens* 2023;49:224–33.
23 Huang C, Tao L, Zhou Y, *et al*. Treated amblyopes remain deficient in spatial vision: a contrast sensitivity and external noise study. *Vision Res* 2007;47:22–34.
24 Marcos S, Moreno E, Navarro R. The depth-of-field of the human eye from objective and subjective measurements. *Vision Res* 1999;39:2039–49.

25 Chin MP, Chu PHW, Cheong AMY, *et al*. Human electroretinal responses to grating patterns and defocus changes by global flash multifocal electroretinogram. *PLoS One* 2015;10:e0123480.
26 Tran N, Chiu S, Tian Y, *et al*. The significance of retinal image contrast and spatial frequency composition for eye growth modulation in young chicks. *Vision Res* 2008;48:1655–62.
27 Chen C-Y, Sonnenberg L, Weller S, *et al*. Spatial frequency sensitivity in macaque midbrain. *Nat Commun* 2018;9:2852.
28 Ramanoël S, Chokron S, Hera R, *et al*. Age-related macular degeneration changes the processing of visual scenes in the brain. *Vis Neurosci* 2018;35:E006.
29 Souza BOF, Abou Rjeili M, Quintana C, *et al*. Spatial Frequency Selectivity Is Impaired in Dopamine D2 Receptor Knockout Mice. *Front Integr Neurosci* 2017;11:41.
30 Luft WA, Iuvone PM, Stell WK. Spatial, temporal, and intensive determinants of dopamine release in the chick retina. *Vis Neurosci* 2004;21:627–35.
31 Zhou X, Pardue MT, Iuvone PM, *et al*. Dopamine signaling and myopia development: What are the key challenges. *Prog Retin Eye Res* 2017;61:60–71.
32 Morgan IG, Jan CL. China Turns to School Reform to Control the Myopia Epidemic: A Narrative Review. *Asia Pac J Ophthalmol (Phila)* 2022;11:27–35.
33 Jansen M, Jin J, Li X, *et al*. Cortical Balance Between ON and OFF Visual Responses Is Modulated by the Spatial Properties of the Visual Stimulus. *Cereb Cortex* 2019;29:336–55.
34 Kremkow J, Jin J, Komban SJ, *et al*. Neuronal nonlinearity explains greater visual spatial resolution for darks than lights. *Proc Natl Acad Sci U S A* 2014;111:3170–5.
35 Güldenagel M, Ammermüller J, Feigenspan A, *et al*. Visual transmission deficits in mice with targeted disruption of the gap junction gene connexin36. *J Neurosci* 2001;21:6036–44.
36 Chen S, Zhi Z, Ruan Q, *et al*. Bright Light Suppresses Form-Deprivation Myopia Development With Activation of Dopamine D1 Receptor Signaling in the ON Pathway in Retina. *Invest Ophthalmol Vis Sci* 2017;58:2306–16.
37 Enaholo ES, Musa MJ, Zeppieri M. *The spherical equivalent*. 2024.
38 Fan Q, Wang H, Jiang Z. Axial length and its relationship to refractive error in Chinese university students. *Cont Lens Anterior Eye* 2022;45:101470.
39 Mannos J, Sakrison D. The effects of a visual fidelity criterion of the encoding of images. *IEEE Trans Inform Theory* 1974;20:525–36.