Investigating the influence of oculomotor functions on the TVPS-4 test of visual perceptual skills in school-age children using machine learning

by

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Abstract

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Introduction:
This study aimed to assess the influence of oculomotor functions and binocularity on visual perception through a standard cognitive test of visual perception. Visual perception, essential for understanding and interacting with the environment, can be affected by impairments that often manifest during childhood and impact academic performance. Although there is evidence suggesting a link between visual perception and binocular vision, research on the exact nature of this relationship is limited. By focusing on school children, this research explored how binocularity and oculomotor functions contribute to visual perception, providing new insights into their potential impact on early cognitive development.

Methods:
A cross-sectional study was conducted with participants recruited from two school centres in Malaysia. Eligible subjects were registered school children aged 6-14 years, with no severe ophthalmic disorders that would prevent them from completing the assessments. Parental or guardian consent was obtained for all participants. Optometric assessments, performed by a trained investigator, included evaluations of binocular vision, visual acuity, vergence, fusional reserve, accommodation, and stereopsis. Visual perception was measured using the TVPS (4th edition). Data were analyzed descriptively using basic statistical methods and the Orange data mining and machine learning software. Associational analyses included Chi-Squared tests, fast correlation-based filter ranking, and Naive Bayes machine learning.

Results:
The study revealed strong and meaningful associations between several oculomotor functions and visual perception parameters measured by the Test of Visual Perceptual Skills (TVPS-4). Phoria at near and stereoacuity showed significant positive correlations with discrimination and sequential memory, while phoria at distance was linked to improvements in spatial relationships and figure-ground perception. Near point of convergence and stereoacuity positively impacted visual closure, and positive relative accommodation was related to enhanced visual memory and form constancy. Although principal components analysis (PCA) could not consolidate the data into single components, the use of machine learning provided valuable insights, identifying key oculomotor functions that are strong predictors of visual perception performance. These findings offer new perspectives for improving clinical decision-making and targeted interventions based on oculomotor function.

Conclusion:
The findings of this study introduce a novel approach to analyzing optometric data and demonstrate the feasibility of using machine learning to predict complex variable relationships in this field. The results provide strong evidence of a significant relationship between binocular vision impairments and visual perception abilities in school children. Notably, phoria and stereopsis were found to have the greatest influence on visual perception.

Acknowledgements

I would like to begin by expressing my deepest gratitude to my supervisor, Professor Stephen Anderson, whose expert advice and guidance have been instrumental throughout my journey in the Doctor of Optometry program. His unwavering support has been invaluable at every stage, from securing ethical approval to conducting the research and writing this thesis. I am truly grateful for his mentorship and dedication.

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I am immensely grateful to my family for their constant encouragement and love, especially my wife, Queenie. Her unwavering support, endless patience, and deep understanding made the completion of both the Doctor of Optometry program and this thesis possible. I could not have accomplished this without her by my side.

Finally, it is my sincere hope that this thesis will make a meaningful contribution, however modest, to the field of optometry.

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Chapter 1. Introduction

1.1 Literature research strategy

To identify studies that have already attempted to explore the relationship between visual perception and binocular vision, a search for evidence was conducted using the online electronic databases of Excerpta Medical dataBASE (EMBASE), Medical Literature Online (MEDLINE) and the Cumulative Index of Nursing and Allied Health Literature (CINAHL). These databases are some of the most popular information sources used to inform health reviews but these were also selected due to comprising extensive indexing to journals covering topics in optometry and ophthalmology (Aveyard, 2023). Moreover, this indexing can provide sufficient cross-coverage of journals as to help capture papers that would be missed when searching a single database alone. Therefore, this approach helped to reduce the risk of searching bias (Bramer et al., 2018). Theoretical data based on bibliographic research implies that the searching of the noted databases would yield a recall accuracy of >90% for articles of relevance to a specific review problem (Bramer et al., 2017). As one could posit that a risk of searching bias in this review could amount to <10%, the search was expanded to encompass Grey literature; this was achieved through searching of Google Scholar and Open Grey (Preston et al., 2015; Adams et al., 2016). This ensured sufficient rigour in the search for pre-existing evidence and therefore, promoting compliance with that expected of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-based reviews (Page et al., 2021).

The search terms were formulated in response to the core aim of this background review: to identify primary research studies that have attempted to explore the relationship between visual perception and binocular function. The simple search phrases were supplemented with all known variant terms and to enhance the precision of the search, a range of modifications were applied to select terms. Such adaptations included truncation syntax (*), mapping of terms to topic headings and combining terms in a series of individual phrases and groups of terms using Boolean logic: operators OR/AND (Aveyard, 2023). The search strategy comprised: [“child*” OR “adolescen*” OR “paediatric” OR “pediatric” OR “minor*”] AND [“visual perception” OR “visual perception” OR “TVPS” OR “test of visual perception”] AND [“binocular vision” OR “binocular*” OR “binocular function”]. A select number of these key phrases were used to perform the search of Grey literature via Google Scholar and Open Grey. In addition, citation screening of all eligible papers was performed to capture any potentially relevant articles that had been incidentally missed by the database searches (Preston et al., 2015). The records retrieved were then filtered using inclusion and exclusion criteria (Appendix 1). Papers were limited to a primary research design of a quantitative methodology, English language and publication in the past 20 years. These criteria were used to ensure the findings would support the review aim and promote the generation of background evidence that remains of value to current optometric practices and therefore, providing rationale to warrant the researched conducted herein. All studies also had to comply with select population criteria, in order to remain generalisable to the target population group" school children aged 6-14 years. There was also a need to focus upon capturing studies that have previously used the TVPS to measure visual perception function and in using this information to support associational testing with binocular function, and/or, optometric measures thereof. These papers were given additional weight in the synthesis that proceeds this section. The merits and limitations of eligible papers were appraised in line with critical appraisal expectations and the key findings were formulated based on the guidance for synthesis in reviews without meta-analysis (Campbell et al., 2020; Al-Jundi and Sakka, 2017).

1.2 Overview

This thesis aims to explore the association between binocular vision and visual perception using the TVPS in children of school age (6-14 years). This aim was devised in response to key knowledge gaps in the field and due to a paucity of studies having explored this relationship. This work was completed to assist in advancing knowledge in the field and to assist in the prediction and management of visual perception deficits in children with a range of binocular vision problems. Such earlier detection and management may assist in mitigating the adverse impacts of both binocular and visual perception dysfunction upon child development and education, which usually imparts a life-long impact upon health, wellbeing and prospects.

The introductory chapter provides the context and rationale for the research undertaken, commencing with a background of the extent and burden of binocular vision disturbances, the physiology of visual perception and the impact of visual dysfunction upon children. This is followed by a review of the literature to demonstrate what is already known in the field and to elicit the evidence gap that this research aimed to resolve. The introductory chapter terminates with the core research aim, objectives and hypotheses. The second chapter provides the details and justification for the methodology and methods used to explore the association between binocular vision and visual perception, while the third chapter presents the key findings using an artificial intelligence methodology that involved feature selection and Naïve Bayes supervised machine learning. The fourth chapter provides a discussion of the findings in light of pre-existing literature and the wider evidence base, including a critical evaluation of the results in view of the merits and limitations of the research study. This is followed by the implications and recommendations for ongoing optometric practices and related guidelines for vision screening in school age children. The final chapter provides a general summary of the work, along with the key avenues for future research in the topic area.

1.3 Visual perception function

Visual perception comprises several key elements for efficient interaction with the environment and for the completion of fine spatio-temporal activities associated with daily living, including: 1) discriminative ability, 2) visual memory, 3) visual-spatial ability, 4) visual form constancy, 5) figure ground, 6) visual sequential memory and 7) visual closure (Schwartz, 2017). The importance of visual perception is also reflected in the hierarchy of visual function (Figure 1), as originally proposed by Warren (1993). This shows a hierarchy of visual functions related to the development of visual skills. The foundational functions influencing perception, according to this model, include oculomotor control, visual fields and visual acuity. This is followed by attention to scan and focus on information received by, and scanning the environment for key visual attributes such as form constancy, figure ground discrimination, visual closure, visual organisation and spatial orientation. The highest skill is visuocognition in which individuals can use visual perception information alongside other sensory inputs to understand and complete various tasks.

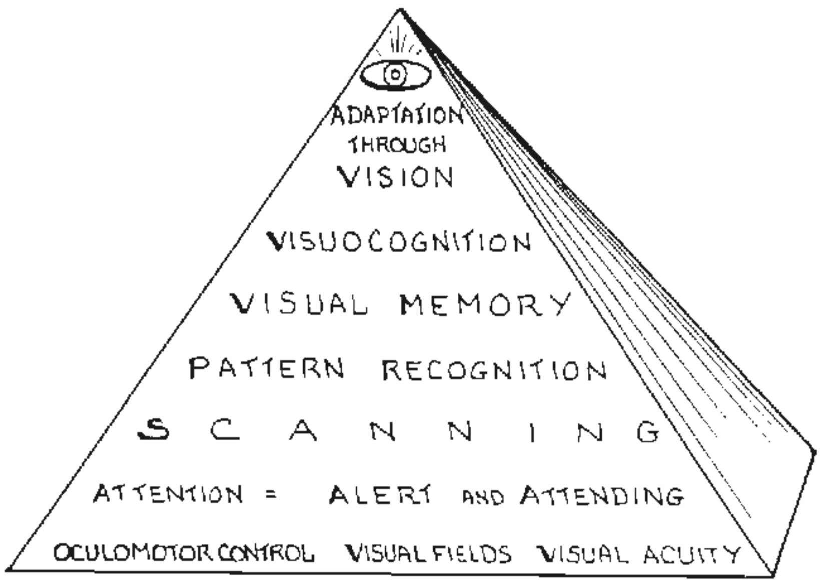


Figure 1 Hierarchy of visual functions requiring for visual perception skill development and utilisation (Warren, 1993).

The various components of visual perception are denoted for contextual purposes. Figure 2 illustrates examples of simple methods for assessing perceptual functions, extracted from the TVPS-4. Form constancy refers to the ability to identify and distinguish objects independent of variances in size, colour, shape, position and/or texture (2a), while figure ground is the ability to distinguish foreground from background (2b). Visual closure refers to the ability to identify objects that are partly obscured or missing (2c) and visual memory is the ability to receive a visual stimulus, retain the information and store the information for later retrieval and use (2d). Visual discrimination refers to the ability to recognise similarities and differences in the shape, size, colour, object and patterns (2e) and visual sequential memory is the ability to memorise and recall a sequence of objects or events in the demonstrated order (2f). Finally, visual-spatial ability is the ability to perceive two or more objectives in relation to each other and oneself (2g).

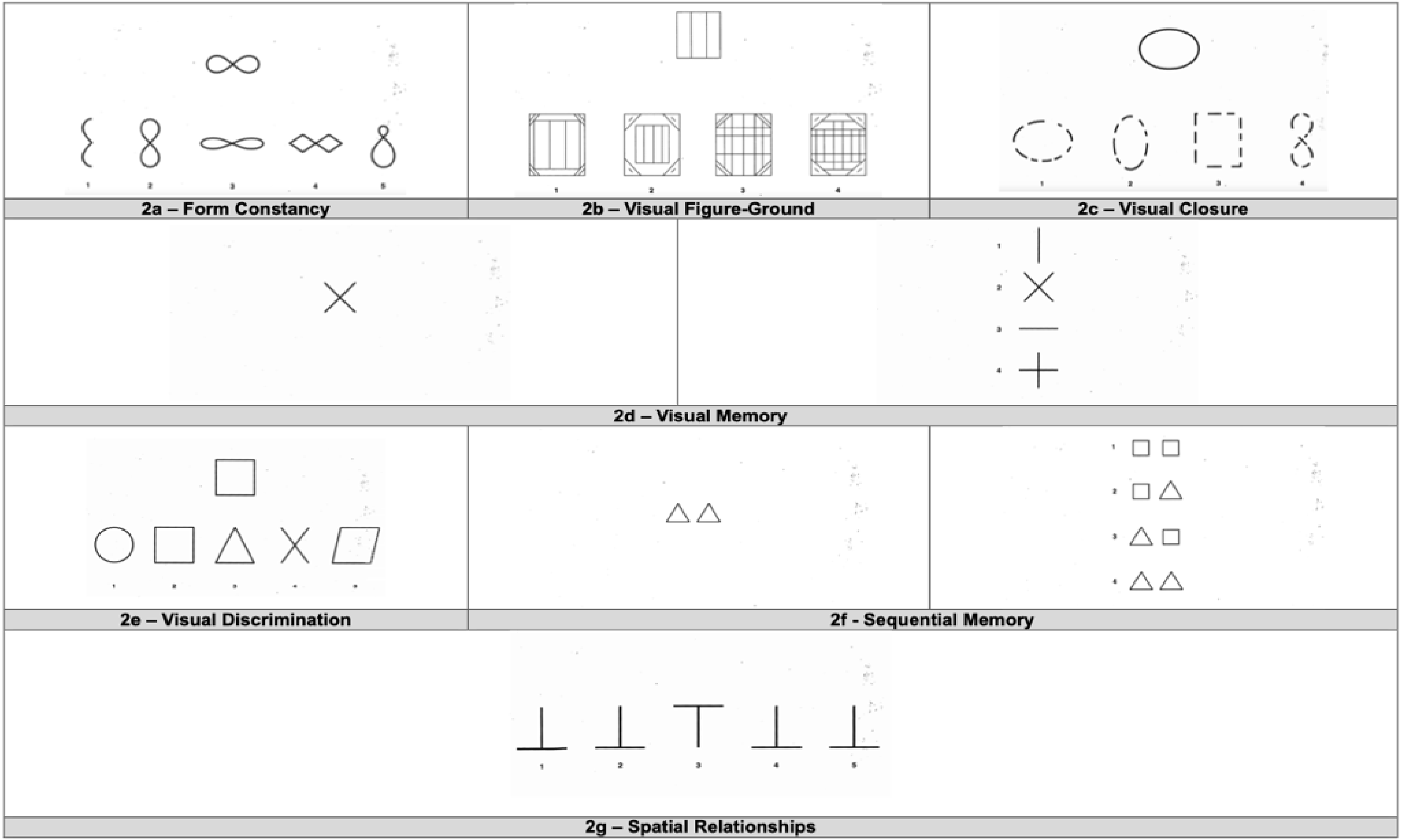


Figure 2 Examples of Perceptual Function Tests from the Test of Visual Perceptual Skills 4th Edition (TVPS-4).

Disturbances of vision can place a greater burden on individuals. Problems with visual perception are mostly attributed to specific impairments of visual system anatomy and/or pathways that receive visual information but they can also arise due to central neurobiological dysfunctions of the visual system (Girkin and Miller, 2001). Central contributions to disturbed visual perception tend to comprise lesions of the cortico-cortical and cortico-subcortical pathways, which are involved in bridging perception information to other cognitive functions, such as memory and emotion (Girkin and Miller, 2001).

There is further complexity in understanding visual perception and disorders thereof, due to marked inter-individual variances in the processing and actioning of information received. This variance is thought to be a product of genetic and epigenetic factors affecting biomolecular responses to stimuli, as well as expectations or learned probabilities concerning the external environment, context and social-based cues, previous or historical visual and cognitive memories and random fluctuations or firing of neuronal signals within brain regions implicated in the processing of visual information (Partos *et al.*, 2016).

The complexity of visual perception can be understood through, for example, the phenomenon of facial perception and the individual variances in this process. Faces are among the most informative and visually significant stimuli humans perceive. Even a fleeting glimpse of a person's face can convey a vast amount of information about the external world, the behaviours of others and our non-visual perceptions thereof. Perception of faces involves recognizing subtle amalgamations of tissue-like objects, such as the eyes, nose, and eyebrows. This recognition can be distorted by additional visual cues, such as position and illumination (Tsao and Livingstone, 2008). Functional magnetic resonance imaging (fMRI) studies have shown that face recognition activates specific areas within the fusiform regions, including the superior temporal sulcus, the occipital face area and the fusiform face area of the lateral right mid-fusiform gyrus (Tsao and Livingstone, 2008; Atkinson and Adolphs, 2011). Understanding these neural mechanisms highlights the intricate nature of visual perception and underscores the importance of studying individual differences in facial perception.

Issues in face recognition have been recognised across a range of pathologies affecting varied organ systems including traumatic brain injury, stroke, encephalitis, macular degeneration, dementia and schizophrenia (Corrow *et al.*, 2016). Therefore, perception, in its complex form, demands a series of integrative functions of both ocular and extra-ocular systems.

Interestingly, personality and a range of factors that influence personality have also been shown to account for some variances in visual perception, highlighting that even seemingly non-disparate central inputs can affect perception of the external world (Smith *et al.*, 2012). This can create challenges for assessing visual perception skills from an optometric perspective, both in terms of inter-assessor reliability and regarding the validity of measuring the core visual perception functions: discrimination, visual memory, visual-spatial relationships, form constancy, figure ground, sequential memory and visual closure (Schwartz, 2017). While cognitively mature persons encounter such high complexity in the processing of visual perception information, children may encounter lesser influences due to the majority of information being used to perceive the world emerging from visual information, as opposed to visual and cognitively stored or interpreted information that may be influenced by prior life experiences. However, children who acquire disturbances of visual perception may encounter significant impediments in life due to the adverse impact upon development and education (Davis *et al.*, 2005; Zhang *et al.*, 2021a). In a recent cohort study of 1,050 elementary school children aged 6-13 years in China and with below-average scores in mathematics, Zhang *et al.* (2021a) explored the relationship between said ability and visual and auditory perception functions. The results showed that impaired visual perception incurred a more deleterious impact upon mathematical ability compared to those with dysfunction of auditory perception. In addition, mathematical ability was significantly poorer among children with disturbances of visual perception compared to controls who did not have such issues. The measure of visual perception was based on the widely accepted Developmental Test of Visual Perception – version 2 (DTVP2).

DTVP2 comprises eight subdomain tests, which include position in space, figure-ground, visual closure, hand-eye co-ordination, copying, spatial relationships, visual-motor speed and form constancy. However, the internal consistency of these measures has been quite varied, therefore posing potential issues of measurement bias for some visual skills. In a sub-analysis of the data, compared with normal control subjects, children with below-average mathematics scores had significantly poorer hand-eye co-ordination, spatial relationships and spatial localisation abilities. However, the other domains of the DTVP were comparable between groups from a statistical perspective. A key limitation to this research was the failure to assess a broader range of visual and cognitive functions among the children. This precludes insight into the proportion of the variance in impaired mathematical ability that were accounted for by visual perception problems.

A range of other studies have demonstrated associations between distorted visual perception and poor academic performance (Cui *et al.*, 2017; Pieters *et al.*, 2012; Lee, 2022). Lee (2022) showed that handwriting legibility among children aged 6-9 years was significantly related to hand-eye co-ordination, coping, figure-ground segmentation and spatial relationships on the DTVP. Pieters *et al.* (2012) found that children aged 7-9 years with mathematical difficulties have significantly worse visual perception test scores of the Visual-Motor Integration test, which reflects a copying-type test and thus congruent with that of the DTVP. Similarly, Cui *et al.* (2017) showed that visual form perception was significantly associated with numerosity and digit comparisons.

Several other studies have also identified consistency in the relationship between impaired visual perception function and academic performance in children of school age (Zhou *et al.*, 2015; Zhou *et al.*, 2020; Cui *et al.*, 2024; Cui *et al.*, 2019; Williams *et al.*, 2011). Importantly, Zhou *et al.* (2020) showed that visual form was significantly predictive of mathematical attainment over a 3-year period (Figure 3), showing how disturbances of visual perception can adversely impact education in the long term. Overall, this work highlights the importance of understanding the contributions of dysfunctional visual perception skills to the educational prospects of school children. It also indicates a key need to explore the association between perception and other more foundational or basic visual motor functions.

	1	2	3	4	5	6	7	8
1. Mathematical achievement	–							
2. Figure matching (RT)	0.34*	–						
3. Figure matching (ACC)	0.27*	0.61*	–					
4. Numerosity comparison (RT)	0.09	0.40*	0.17*	–				
5. Numerosity comparison (ACC)	0.26*	0.57*	0.40*	0.63*	–			
6. Choice reaction time (RT)	−0.13	0.08	−0.05	0.40*	0.17*	–		
7. Choice reaction time (ACC)	0.18*	0.23*	0.20*	0.20*	0.25*	0.27*	–	
8. Mental rotation	0.18*	0.13	0.14	0.02	0.14	−0.19*	0.10	–
9. Nonverbal matrix reasoning	0.00	0.20*	0.30*	0.22*	0.36*	0.09	0.11	0.17*

ACC accuracy rate, *RT* reaction time

* $p < 0.05$

Figure 3 Summary of Person correlations for the study in the study of Zhou et al. (2020).

One basic visual function of interest with possible inter-relatedness to visual perception is binocular vision. This is the ability to perceive depth of objects in time and space, allowing a three-dimensional view of the world. Binocular vision is therefore, reflective of the function of stereopsis, which is the ability to resolve monocular disparities in visual information received by the left and right eyes (Read, 2015).

1.4 Binocular Vision and the Epidemiology of Binocular Dysfunction

As binocular vision requires information that is received by both eyes and is processed in a functional (non-pathological) way, visual deficits affecting one or both eyes, can lead to disturbances of such vision and therefore, likely incurring issues of visual perception (Zhaoping and May, 2016). The commonest eye disorders associated with impaired binocular vision include strabismus (ocular malalignment) and amblyopia (unilateral or bilateral reduction in best-correct visual acuity due to form deprivation, impaired binocular function or both) (Kaur *et al.*, 2023; Zhang *et al.*, 2021b). Detecting these problems of binocular vision in early life, along with potentially co-existing perceptual problems, is important for informing optimal ophthalmic treatment.

In keeping with the adverse consequences of visual perception, disorders of binocular vision have been shown to negatively affect academic performance among school children (Wood *et al.*, 2018; Alvarez-Peregrina *et al.*, 2021; Alvarez-Peregrina *et al.*, 2020). In children aged 8-10 years, Wood *et al.* (2018) showed that stereoacuity was significantly associated with academic performance scores for reading, writing, spelling, grammar and numeracy. An even stronger influence upon scores was noted for visual sequential memory. Alvarez-Peregrina *et al.* (2021) found that binocular dysfunction was significantly associated with poor academic performance (Figures 4-6). Tian *et al.* (2024) also explored the association between academic performance and diagnosed binocular vision problems. They showed that there was a progressive negative correlation between stereoacuity and academic attainment among Chinese primary school students aged 6-12 years.

	TOTAL			BAD Academic Performance			GOOD Academic Performance			p-Value	Difference ± SE (95% CI) *
	n	Mean ± SD	Median [IQR]	n	Mean ± SD	Median [IQR]	n	Mean ± SD	Median [IQR]		
Monocular VA (RE)	10192	0.92 ± 0.15	1.00 [0.10]	1000	0.88 ± 0.18	1.00 [0.20]	9192	0.93 ± 0.14	1.00 [0.10]	**<0.001**	**−0.05 ± 0.00 (−0.06–−0.04)**
Monocular VA (LE)	10201	0.90 ± 0.16	1.00 [0.10]	1003	0.84 ± 0.20	0.90 [0.20]	9198	0.91 ± 0.16	1.00 [0.10]	**<0.001**	**−0.07 ± 0.01 (−0.08–−0.06)**
Binocular VA near distance	7042	0.97 ± 0.09	1.00 [0.00]	650	0.94 ± 0.13	1.00 [0.10]	6392	0.97 ± 0.09	1.00 [0.00]	**<0.001**	**−0.03 ± 0.00 (−0.04–−0.03)**
NPC (cm)	9729	5.51 ± 5.55	5.00 [7.00]	934	6.47 ± 6.08	5.00 [9.00]	8795	5.40 ± 5.49	5.00 [7.00]	**<0.001**	**1.06 ± 0.19 (0.69–1.44)**

* Difference ± standard error (and its 95% confidence interval) calculated as the mean of participants with "bad academic performance", minus the mean of participants with "good academic performance". Significant differences ($p < 0.05$) are shown in bold.

Figure 4 Summary of results presented by Alvarez-Peregrina et al. (2021).

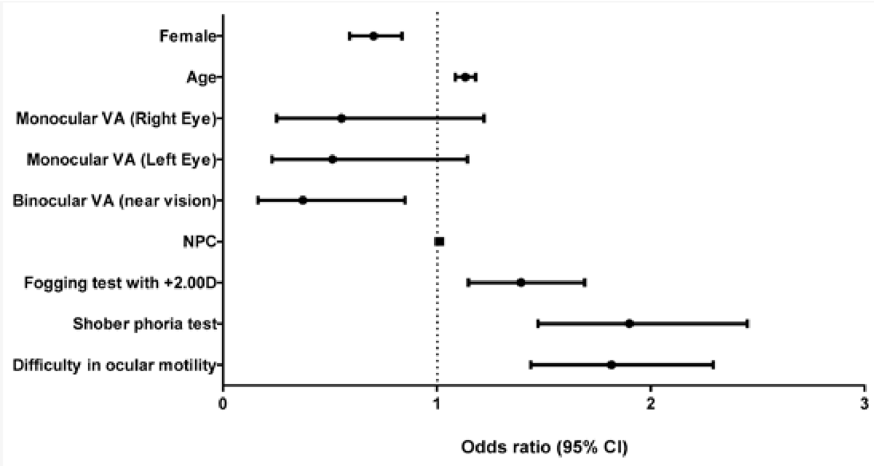


Figure 5 Summary of results presented by Alvarez-Peregrina et al. (2021).

Poor Academic Performance	Odds Ratio	Std. Err.	z	*p* > z	[95% Conf.	Interval]
Female	0.704	0.062	−3.980	<0.001	0.593	0.837
Age	1.133	0.025	5.770	<0.001	1.086	1.182
Monocular VA (Right Eye)	0.554	0.223	−1.470	0.142	0.251	1.220
Monocular VA (Left Eye)	0.512	0.210	−1.630	0.102	0.229	1.143
Binocular VA (near vision)	0.374	0.157	−2.350	0.019	0.164	0.851
NPC	1.011	0.007	1.500	0.133	0.997	1.026
Fogging test with +2.00 D	1.394	0.138	3.360	0.001	1.148	1.692
Shober phoria test	1.900	0.247	4.940	<0.001	1.473	2.452
Dificulty in ocular motility	1.817	0.215	5.040	<0.001	1.440	2.292

Figure 6 Summary of multiple regression analysis presented by Alvarez-Peregrina et al. (2021).

Poor academic performance associated with strabismus, amblyopia and other problems of binocular vision have also been reported elsewhere (Khalaj *et al.*, 2011; Gitsels *et al.*, 2020; White *et al.*, 2017). The problem of disordered binocular vision is also reflected in studies exploring the impact of corrective surgery for strabismus where significant improvements in reading ability among children aged 5-14 years were achieved, see Figures 7-8 (Ridha *et al.*, 2014). In contrast, however, Horvat-Gitsels *et al.* (2023) explored the educational trajectories of school children aged 7-16 years with strabismus and amblyopia but failed to find a difference in performance in English, Maths and Science at any stage. This study, however, did not attempt to assess visual perception or other optometric problems.

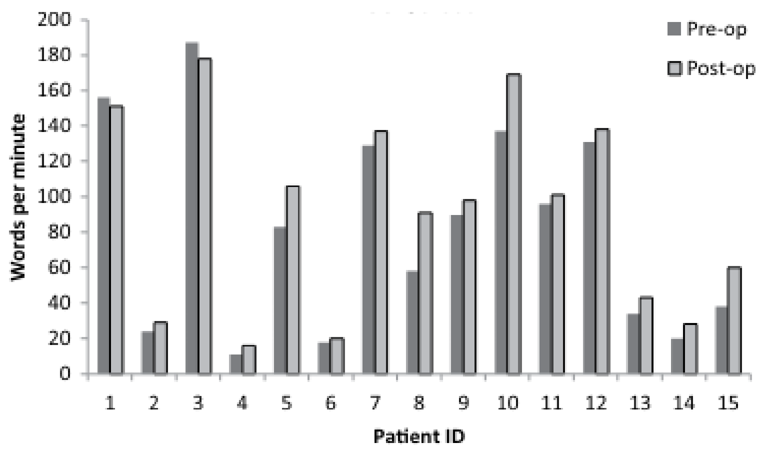


Figure 7 Overview of the improvements in reading ability for word count per minute for children who underwent strabismus surgery (Ridha et al., 2014).

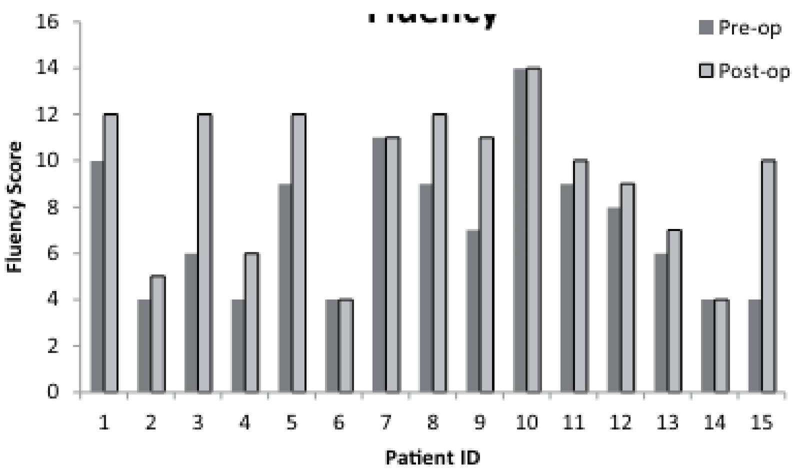


Figure 8 Overview of the improvements in reading fluency for children who underwent strabismus surgery (Ridha et al., 2014).

Visual problems in school children often go undetected, leading to adverse life-long impacts (Bountziouka *et al.*, 2021). In a population-based study conducted in Ireland, Harrington *et al.* (2022) showed that 68% of under-performing school children had not received an eye examination within the preceding 12 months and reported a significant association between poor academic performance and observed eye problems.

Problems of binocular vision tend to be detected prior to those of visual perception in view of the clearer ophthalmic signs and symptoms of binocular over perceptual dysfunctions (Griffin and Grisham, 2002). In the UK, the introduction of universal childhood vision screening has led to the improved detection and treatment of various vision problems. However, while such screening may be positioned to detect issues of binocular vision, such as amblyopia, there is no standardised means to assessing visual perception (McCullough and Saunders, 2019). Moreover, application of the screening criteria to a cohort of 294 children showed that the tests had only modest to high accuracy in detection of visual problems (McCullough and Saunders, 2019). Therefore, a considerable number of children may be living with unrecognised visual perceptual problems and this may contribute to ongoing issues in development and education. Based on the review of the results, it can be suggested that an effective approach to vision screening might include incorporating a visual perception test when disorders of binocular vision are detected.

Understanding the intricate relationship between binocular vision and visual perception is crucial for guiding ongoing research and contributing vital evidence to practice, guidelines and policy decisions. This research is particularly important given the high prevalence and significant burden of vision problems among school age children.

Data from the International Agency for the Prevention of Blindness revealed that over 450 million children worldwide have some form of visual impairment, representing nearly 25% of the global child population (Vision Atlas, 2023). Visual problems contribute to more than half a million disability-adjusted life years, a widely accepted measure of disease morbidity (Abdolalizadeh *et al.*, 2021). This makes visual problems in children one of the leading non-communicable causes of disease burden, especially in high-income countries where communicable diseases are less prevalent (WHO, 2023).

Research into the epidemiology of binocular vision problems highlights the value of further study in this area. A meta-analysis of 56 papers involving 229,000 individuals found that the prevalence of strabismus was almost 2.0%, with exotropia (1.23%) being more common than esotropia (0.77%) (Hashemi *et al.*, 2019). Amblyopia is similarly common and burdensome, with another meta-analysis showing a global prevalence rate of 1.44%. Notably, the prevalence is higher in Europe and North America (2.4-2.9%) compared to Asia and Africa (<1.1%) (Fu *et al.*, 2020). The mean prevalence indicates that around 100 million people currently have amblyopia, with projections suggesting this number could rise to 220 million by 2040 due to population aging.

These epidemiological projections underscore the importance of advancing knowledge in this field to inform initiatives and develop treatments that can prevent or better manage visual problems on a large scale. In the UK, data on child visual impairment is less comprehensive, but estimates from 2015 indicate that over 25,000 children aged 0-16 years live with some form of visual impairment requiring specialist educational support due to these problems and/or other cognitive or intellectual issues (National Sensory Impairment Partnership, 2015).

Overall, research into the connection between binocular vision and visual perception has significant implications for improving the quality of life for children globally, potentially leading to meaningful advancements in managing and preventing vision problems.

1.5 Narrative Synthesis

Overall, there has been a relative paucity of research having explored the association between visual perception and binocular vision and therefore, the evidence has been discussed in some depth. This was performed to reveal the persistent gaps and uncertainties in the knowledge base as to justify the research in this work. A summary of the papers included in subsections 1.4.1 and 1.4.2 is provided in Appendix 2.

1.5.1 Studies using TVPS

In a recent prospective observational study, Ibrahimi *et al.* (2021) explored the impact of strabismus and amblyopia upon the visual perception and visual-motor skills of children of ages 5-15 years. Children in the study were limited to those with primary strabismus but no prior optometric treatment except for refractive correction. In addition, children were also required to have a best-correct visual acuity of >20/100 and have an average intelligence quotient for their age, which was necessary to ensure sufficient comprehension and completion of the visual perceptive and visual-motor tests. Acuity and strabismic measures were taken to inform new corrective treatment and the diagnosis of strabismus was also affirmed by an ophthalmologist to avoid a risk of diagnostic ascertainment bias. Visual perception function was measured using the TVPS (third edition), while visual-motor ability was assessed using the Visual-Motor Integration (VMI, sixth edition). Dysfunction of binocular vision was reflected in the restriction of subjects to those with strabismus and the extent of the association with visual perception was based on the extent of esotropia and exotropia.

Among subjects with esotropia, form constancy progressively decreased across four subgroups (Figure 9), with poorer scores seen in those with impaired accommodation and lack of stereopsis. The findings suggest that children with accommodative esotropia have better visual perception compared to those with persistent partial or absent accommodation and no stereopsis. Additionally, the degree of stereopsis appears to significantly affect visual perception, while variations in esotropia severity have a lesser impact. A gender difference was observed in visual closure among children with esotropia and in sequential memory among those with exotropia (Figure 10). For children with exotropia, a significant difference in form constancy was found between subgroups. Those with intermittent exotropia and slight stereopsis reduction, as well as those with normal stereoacuity, achieved the highest form constancy scores (Figure 11), while children with markedly reduced stereopsis or dissociated exotropia had the lowest scores. Stereopsis also had a significant effect on visual memory in comparison to those without stereopsis.

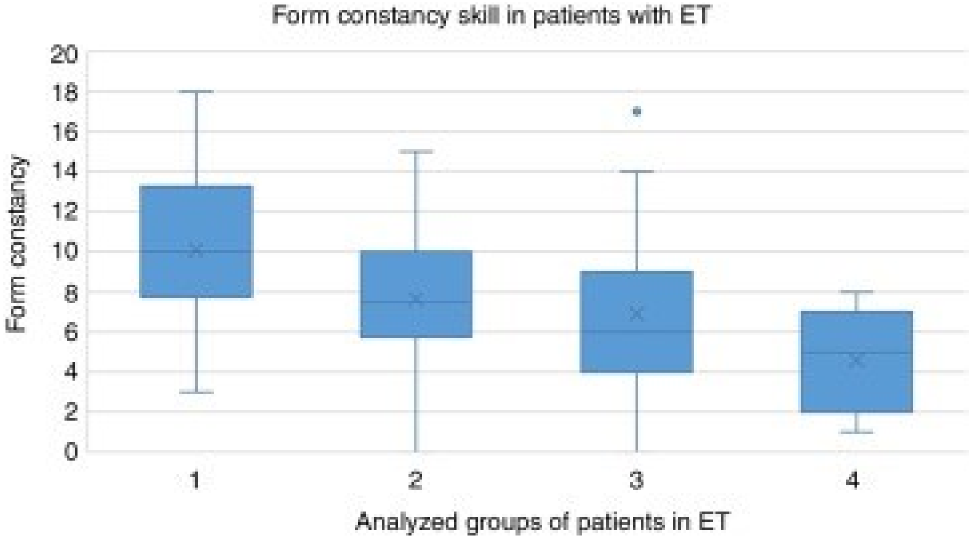


Figure 9 Summary of form constancy scores in persons with esotropia (Ibrahimi et al., 2021).

Variables for esotropia	Patients (n = 79) Mean ± SD	Boys (n = 48) Mean ± SD	Girls (n = 31) Mean ± SD	p-Value[a]
Visual closure	8.3 ± 3.6	9.1 ± 3.6	7.1 ± 3.3	0.019
Motor VMI	90.0 ± 15.6	94.7 ± 14.0	83.2 ± 19.6	0.003
Variables for exotropia	**Patients (n = 67) Mean ± SD**	**Boys (n = 39) Mean ± SD**	**Girls (n = 28) Mean ± SD**	**p-Value[b]**
Sequential memory	9.1 ± 3.3	9.9 ± 3.4	8.0 ± 3.0	0.005
General VMI	93.7 ± 13.9	96.3 ± 12.4	90.0 ± 15.1	0.017

Figure 10 Summary of gender variances in visual perceptual and visual motor abilities (Ibrahimi et al., 2021).

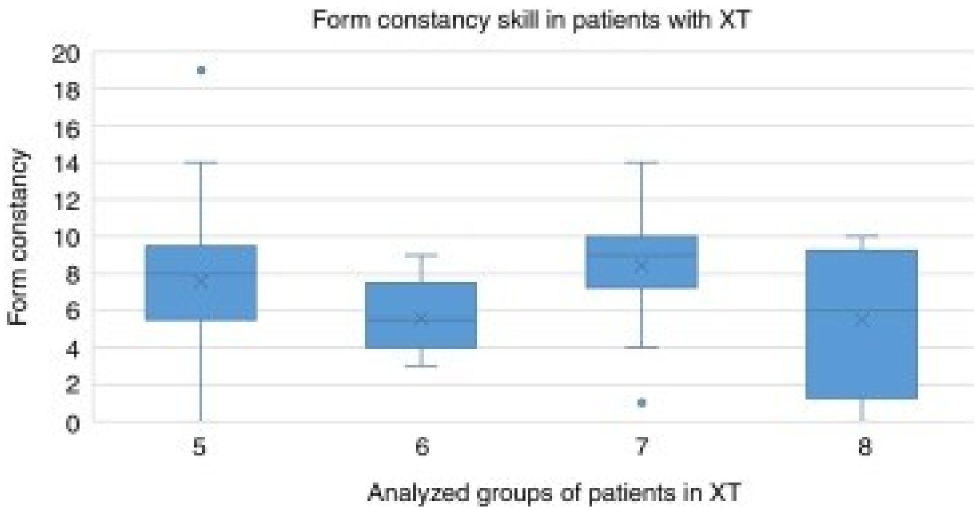


Figure 11 Summary of form constancy scores in persons with exotropia (Ibrahimi et al., 2021).

Gender significantly influenced scores in the figure-ground and visual closure subdomains of the TVPS, with males showing better performance than females. However, these gender differences may be unreliable due to the small sample size and the risk of a type II error. In a further sub-analysis, children without amblyopia had significantly higher spatial relationship and visual closure scores compared to those with unilateral or bilateral amblyopia (Figure 12). Those with unilateral amblyopia scored better in spatial relationships than those with bilateral amblyopia, although this was not the case for visual closure. The significance of the difference in visual closure scores between children without amblyopia and those with amblyopia was unclear (Figure 13). Additionally, older children (aged 10-15 years) performed better across various TVPS domains than younger children (under 10 years), suggesting that cognitive maturity and age may influence the relationship between binocular vision and TVPS scores.

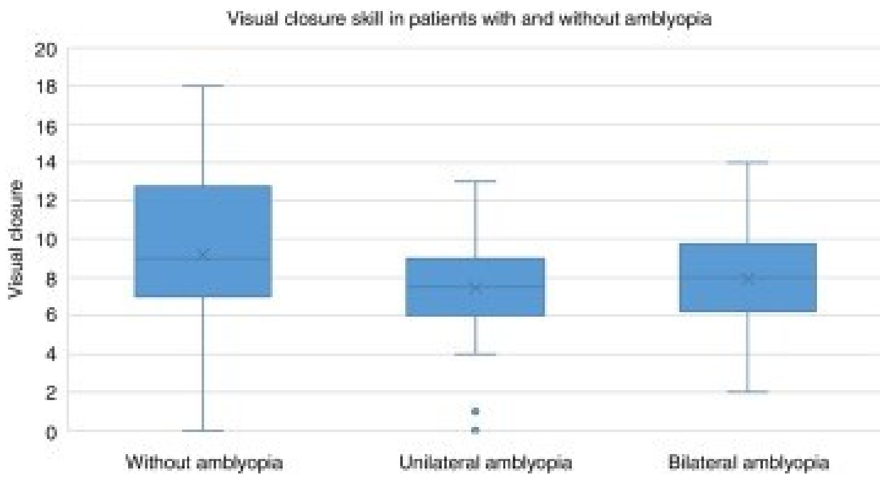


Figure 12 Summary of visual closure scores in relation to amblyopia (Ibrahimi et al., 2021).

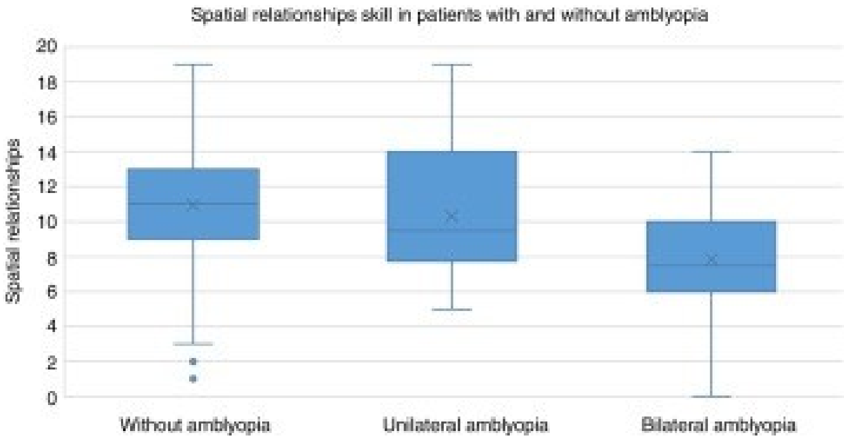


Figure 13 Summary of spatial relationship scores in relation to amblyopia (Ibrahimi et al., 2021).

In a study by Ho et al. (2015), the relationship between vision and visual perception was explored in children aged 4-7 years in Hong Kong. However, as almost half the participants were under 5 years of age, caution is needed when interpreting the findings, as younger children may lack the maturity required for accurate visual assessments. Similar to the study by Ibrahimi et al. (2021), visual perception was assessed using the third edition of the TVPS. The study found a 3.4% rate of visual perception dysfunction, with variations across sub-domains ranging from 2.2% for spatial relationships to 10.6% for form constancy. Near visual acuity was significantly associated with visual discrimination and spatial relationships, though these factors accounted for only 1-3% of the variance in visual perception. No significant associations were found between visual acuity and visual memory or form constancy. Further comparisons between TVPS and other visual functions were limited due to the small sample size of children with specific visual deficits, highlighting a key limitation of the study and the need for further research to better understand the link between binocular vision and visual perception.

Two other studies assessed visual perception in children with strabismus and binocular dysfunctions using the TVPS. Argilés et al. (2023) conducted a retrospective analysis of 110 children aged 6-14 years with strabismus, amblyopia, or other binocular vision dysfunctions. The children were divided into three groups: those with strabismus and/or amblyopia, those with other binocular dysfunctions as defined by Scheiman and Wick (2019), and a control group with healthy, age- and gender-matched vision. Visual perception was evaluated using the third edition of the TVPS, consistent with other studies in this subsection. No significant differences were found between the strabismus/amblyopia group and controls in visual discrimination, visual memory, spatial relationships, visual constancy, figure-ground, or visual closure. However, a marginally non-significant difference in visual sequential memory was noted, with the strabismus/amblyopia group showing considerably poorer performance. Although this result did not reach statistical significance at the conventional 0.05 threshold, it may be due to the small sample size and insufficient statistical power. Similar trends were observed when comparing controls with children who had other binocular dysfunctions, suggesting that binocular vision plays an important role in visual sequential memory. These findings, however, should be interpreted cautiously, given the limitations of small sample sizes, underpowered analyses, and potential biases from baseline heterogeneity.

Hård *et al.* (2004) aimed to assess the visual perception of school-age children who were born prematurely and had lesions in the posterior visual pathways or exhibited ophthalmic signs indicative of such pathology. The primary brain lesions included cerebral paresis or peri-ventricular leukomalacia. The study included 91 children, aged 5-12 years with a mean age of 6.7 years, making this a valuable population for the research. Of these children, 50.5% had strabismus, indicating impaired or likely impaired binocular vision. Visual perception was assessed using the first revised edition of the TVPS, which may result in some measurement variances compared to earlier studies. The results showed that 67% of the subjects scored below the third percentile on the TVPS, indicating impairments in visual perceptive function. When the cohort was limited to those with known brain lesions, 87% scored below the third percentile, and 84% of this group had binocular vision dysfunction based on the presence of strabismus. Furthermore, the authors reported that good visual acuity did not mitigate poor TVPS results, suggesting that intact or near-normal acuity might not be sufficient to preserve visual perception in children with disturbed binocular vision.

1.5.2 Studies using non-TVPS measures of Visual Perception

Two earlier case-control studies have used the TVPS to explore its relationship with some optometric functions, although there has been less focus on those related to binocular vision. The first study by Cavézian *et al.* (2013) examined the visual and attentional skills of 24 children aged 4-7 years with various ophthalmic problems and compared them to a healthy cohort of 60 controls. The children in the former cohort had disorders including strabismus, amblyopia, cataract, nystagmus, and refractive issues, indicating that many likely had impairments in binocular vision, especially those with amblyopia and strabismus. Indeed, 17 of the 24 children (70.8%) had strabismus and/or amblyopia at baseline, providing sufficient numbers to infer some links to visual perception issues. The subjects were age-matched to controls, limiting comparative bias, which is a common issue in case-control research. Participants completed several visuo-attentional tasks designed to assess visuo-spatial deficits, spatial working memory, local and global attention, and visual perception. Perception was assessed using a specific shape-matching task involving a series of variant shapes in terms of geometry and shading. Subjects had to match a selected symbol against the correct one among six variants, which is a relatively simple measure of visual perception and crude perceptive function. Thus, the study may have underestimated the extent of visual perception problems, particularly in the absence of using the TVPS. The findings showed that the controls performed in line with age-expected results for each test, with a general improvement in scores with advancing age. In contrast, the cohort with visual problems had significantly inferior scores for the visual perception test and took longer to complete the test. Although the test cohort predominantly comprised children with disorders of binocular vision, the small sample size limits the validity and generalizability of the findings to the target group. Additionally, the visual perception test used in this study was unvalidated and potentially prone to measurement bias. It is also likely that the associational analyses were underpowered and thus subject to type II error.

In the earlier case-control study by Cavézian *et al.* (2010), the authors assessed the value of various visuo-attentional tests in evaluating the abilities of children with multiple ophthalmic disorders and some with neuro-visual deficits. Most children in the ophthalmic group had issues resulting in impaired binocular vision, including strabismus and amblyopia, as well as cataracts, macular exudation and retinal detachment. Children in the neuro-visual group had conditions such as visual agnosia and optic ataxia, which are less relevant to this study's focus on binocular dysfunction. The sample sizes differed significantly across groups, with 110 controls compared to only 13 children with ophthalmic disorders. This disparity could lead to comparative bias and limits the generalizability of the findings to the target population of children with binocular vision impairments. Two additional tests of visual perception were used in this study compared to the later case-control study discussed previously. These tests included the shape-matching test, visual memory and an embedded figures test. However, these tests were unvalidated, raising concerns about measurement bias. Despite these concerns, the findings indicated impaired visual perceptive function in the test group compared to the healthy controls, as reflected by less favourable scores on all three tests: visual memory, embedded figures and shape-matching. However, the differences were not statistically significant, likely due to the small sample size, suggesting a potential type II error. Neither of these studies opted to use the TVPS, thereby offering limited insight into the relationship between binocular vision and visual perception.

In another study, Gligorović *et al.* (2011) explored the association between strabismus and stereoacuity upon a range of non-verbal abilities of children aged 7-15 years. The Acadia Developmental Abilities Test was used to assess non-verbal abilities with visual perception being centred upon tests of visual memory and visual discrimination. Children with strabismus and/or impaired stereopsis were included in the analyses. The findings showed that children encountered significantly reduced scores for the visual memory and visual discrimination, relative to expected or normal scores. However, there was a trend with younger aged children observing poorer visual perception, than older children, although the difference was marginally insignificant. Children with preserved visual acuity encountered significantly better visual memory, than those with impaired acuity, while children with strabismus encountered significantly disordered visual memory, than those without strabismus, implying a direct link between visual perception and binocular vision.

These findings align with those reported by Ibrahimi et al. (2021), who used the TVPS to assess visual perception. The consistency of results reinforces the association of interest; however, it’s important to note that Gligorović et al.'s (2011) findings were based on children with esotropia. For children with exotropia, mean visual memory scores were more favorable, and the difference between children with and without strabismus was not statistically significant. Some analyses in this study may have been underpowered, so caution is needed when interpreting these results due to the risk of a type II error.

Gligorović et al. (2011) also found no significant differences in visual discrimination between strabismic and non-strabismic children, nor in visual memory or discrimination scores between children with and without impaired stereopsis. This contrasts with Ibrahimi et al. (2021), who reported that stereopsis significantly affected visual perception function. These discrepancies could be attributed to differences in visual perception tests—TVPS vs. Acadia—as well as issues with sample size and baseline characteristics of the cohorts. Methodological limitations and a lack of empirical research contribute to uncertainty about the relationship between visual perception and binocular vision. This uncertainty underscores the need for further research, as addressed in this study.

In a more recent case-control study, Sawamura et al. (2018) evaluated the perception of three-dimensional shapes in individuals with strabismus, focusing on the influence of stereopsis and monocular cues. The study included participants with strabismus and stereoacuity, those without stereoacuity, and age-matched controls. However, the participants were young adults, limiting the generalizability of the findings to the pre-school children relevant to this research. Despite the age difference, the study is valuable due to its focus on monocular cues, which have been largely overlooked in other studies.

The visual perception assessment was based on the work of Gillebert et al. (2015) and involved tests for three-dimensional shape perception and feature discrimination. The results showed that individuals with strabismus and stereopsis had significantly poorer accuracy in depth perception compared to controls. Due to a lack of statistical power, comparisons with the group lacking stereopsis were not possible for this depth cue. For all other cues, there were no significant differences between the strabismus groups. These findings suggest that strabismus negatively affects visual perception, consistent with other studies reviewed here, though the role of stereopsis remains unclear due to methodological limitations in the evidence base.

Sawamura et al. (2018) also conducted sub-analyses showing that reduced or absent stereopsis may enhance visual perception by relying more on monocular cues, as this can prevent conflicting signals between binocular and monocular information. An earlier study by Economides et al. (2012) found that strabismus, typically acquired early in life, can reduce visual distortions through the suppression of the unfocused image in the affected eye. In individuals with exotropia, perception was dominated by one eye, while the other eye's image was suppressed, though all participants still perceived the images presented to the deviated eye. These images, however, were perceived to be shifted based on the angle of ocular deviation, highlighting the role of plasticity in visual processing and perception. Participants in Economides et al.'s study ranged from 8 to 60 years old, further limiting the relevance of the findings to the younger population of interest in this research.

1.5.3 Summary and Rationale Statement

Overall, an evaluation of the existing literature reveals key knowledge gaps related to assessing visual perception and understanding the relationship between visual perception and binocular vision in school-age children. Due to the varied methods previously used to assess visual perception, it is necessary to explore the value of the TVPS, as it is one of the most popular and widely utilized measures of visual perception (Bakken *et al.*, 2017).

Regarding the association between binocular vision and visual perception, it remains unclear which types of binocular dysfunction promote visual problems and which specific conditions are linked to impaired perceptual skills across core measures of visual perception, such as discrimination, visual memory, visual-spatial ability, form constancy, visual figure-ground, visual sequential memory and visual closure. Both visual perception and binocular vision are critical aspects of visual information processing necessary for understanding and functioning within the external world (Ciuffreda, 2017).

In one study exploring the value of binocular vision, Tabrett and Latham (2012) showed that the binocular visual field was significantly associated with vision-related activity limitations. Moreover, binocular vision significantly predicted greater ability in reading and mobility tasks, suggesting that binocularity can influence visual perception. However, the existing literature has not sufficiently explored the association between binocular vision, disorders of binocularity and visual perception. This lack of depth is compounded by the variable measures used to assess visual perception, highlighting the need for better standardization using the TVPS.

Importantly, school-age children with visual perceptive problems, including potential co-existing issues with binocularity, may go unrecognized. These issues can negatively impact their development, educational and life prospects and overall quality of life and functioning (Partos *et al.*, 2016; Christian *et al.*, 2018; Alrasheed and Elmadina, 2020; Henriksen and Read, 2016). Given that some of this burden may be remedied through accurate diagnosis and treatment, further research is needed to explore the relationship between binocular vision and visual perception. Addressing these particular questions is crucial for advancing knowledge in this area.

1.6 Research Aims and Objectives

In response to the given rationale, this research aimed to explore the association between binocular vision and visual perception using the TVPS in school children aged 6-14 years. The objectives of the research were as follows:

- To determine whether the TVPS is a suitable measure of visual perception in children
- To elicit the optometric parameters that influence TVPS scores
- To identify the nature of the association between binocular vision and visual perception, as assessed using the TVPS measure
- To formulate implications and recommendations for ongoing optometric practices, guidelines and policies for vision screening in children
- To identify avenues for future research in the topic area

Chapter 2. Methods

2.1 Design

To explore the association between binocular vision and visual perception in school-age children and identify other optometric parameters influencing visual perception based on the TVPS, a cross-sectional research design was used (Sedgwick, 2014). This design enabled the collection of optometric data from subjects at a single point in time, offering a narrow temporal insight into the noted association across predefined school-age groups (Maier et al., 2023). To mitigate the issue of intra-rater reliability, data collection was consistent with a point-in-time approach (McHugh, 2012). Thus, the study employed a cross-sectional design rather than an observational cohort, which examines measures over time to identify temporal variations in outcomes (Sedgwick, 2014). Although the lack of temporality in the cross-sectional design is a limitation, the inclusion of various age groups likely captures a range of optometric measures within school-age children.

This research aimed to maximize recruitment by offering a quasi-incentive to parents and their children. Participants received a free comprehensive vision screening assessment (the research procedure) and, for children with vision problems such as impaired acuity, free corrective treatment. This approach provided a natural and ethical incentive, encouraging participation while ensuring the research adhered to ethical principles of beneficence and justice (Varkey, 2021).

2.2 Participants

Participants were recruited from two primary and secondary schools in Kuala Lumpur, Malaysia. These sites were chosen for their convenience to the author and their willing assistance in recruitment by distributing invitations to parents of eligible children. Invitations were sent via postal letters, containing all necessary information about the research, participation expectations, and the rights of parents and children regarding consent and withdrawal (refer to Appendix 3 for the invitation letter sent to the school). This ensured parents could provide valid consent for their children to participate in the optometric assessments. Utilizing the school system to promote and conduct the research also helped build parents' trust. The schools were initially invited to participate through email communication with the primary investigator. This recruitment method aligned with convenience sampling, as it relied on parents providing consent following the invitation.

Children eligible for the study had to be registered at one of the two selected schools and be aged 6-14 years. The lower age limit of six years was chosen because children at this age are expected to have sufficient cognitive maturity and concentration to complete the optometric assessments (Hård et al., 2004). Targeting young children is important since vision problems often manifest early and become evident when children start school and struggle with tasks (Cassetti et al., 2019; Sathyan, 2017). The UK National Screening Committee recommends vision screening starting at ages 4-5, aligning with this study's aim to provide comprehensive assessments (UK NSC, 2023). The upper age limit of 14 years was set because visual perception and binocular function issues typically become apparent through academic performance, disengagement, or self-reported symptoms by adolescence (Bates, 2010). Additionally, around 100 million children under 15 experience visual impairment, justifying the age range for screening (Ali et al., 2021).

There were no restrictions based on academic ability, allowing for a diverse sample, particularly in identifying near-work problems, which could indicate myopia or issues with visual perception and binocular vision (Huang et al., 2015). The exclusion criteria were limited to children with severe ocular or oculomotor disorders, as these conditions would hinder accurate and reliable completion of the assessments for visual perceptive ability, binocular function, and other optometric tests. Additionally, children with intellectual disabilities were excluded due to potential difficulties in completing the optometric tests. Since the optometric tests were conducted at a single point in time, there was no concern about variance from adaptation to changes in refractive prescriptions. Therefore, children with refractive prescriptions were not excluded.

A total of 97 children, aged 6 to 14 years, were recruited for the study. G-Power was conducted using Exact test family with Correlation: Bivariate Normal Model statistical test (Pearson correlation coefficient). A sample size of n=84 was required to obtain an 80% statistical power at a 5% alpha level for a medium effect size ($\rho = 0.30$).

Ethical approval was obtained from the College of Health and Life Sciences Research Ethics Committee of the Aston University. Approval was granted (Appendix 4) following the submission and review of the study proposal. The wellbeing and rights of participants were safeguarded in accordance with the ethical guidelines outlined in the Declaration of Helsinki (World Medical Association, 2018). To ensure confidentiality, participant data was anonymized using a numerical coding system to protect personal identifiable information.

Formal consent was required from all participants, and given the age of the children involved, consent was obtained from their parents (Appendix 5). Parents received information sheets (Appendix 6) detailing the purpose of the research. An age-appropriate information sheet (Appendix 7) and consent form (Appendix 8) were provided to participants for their consideration and informed decision-making. All consent forms had to be signed and dated before the children could participate in optometric testing. Any incomplete or unsigned forms would have delayed or excluded participants from the study, although no such instances occurred.

The research took place during the COVID-19 pandemic, with the author acting as the sole investigator to ensure participant safety. This limited the ability to assess inter-rater reliability for optometric testing but was necessary to comply with health guidelines. Social distancing measures were followed by both the author and participants to reduce the risk of virus transmission. Support and guidance from the academic supervisor were provided via email and video conferencing.

2.3 Procedure and data measures

Basic demographic and relevant clinical data were collected to identify any known confounding or mediating variables (Hulley et al., 2013). This information was gathered through a parent-reported proforma, which included details such as child age, gender, ethnicity, medical and surgical history, and ophthalmic or optometric history. Additionally, data on the educational level and achievements of both children and their parents were recorded to better understand the connection between visual perception deficits and academic performance. Collectively, these diverse data measures facilitated a thorough and insightful evaluation of variable relationships, aiming to have a significant impact on the academic, clinical, and educational communities.

Six key optometric tests were performed to assess various visual functions. A summary of these measures, together with the independent and dependent variables for analytical purposes, are shown in Table 1.

Table 1 Summary of independent and dependent variables.

Optometric Measure	Assessment /Tool	Variable	Data	Duration of Testing
Visual perception	TVPS	Dependent	Continuous	30 mins
Binocular function	Cover testing near and far	Independent	Discrete	1 min
Visual acuity	logMAR and Lea symbols	Independent	Continuous	5 mins
Vergence	NPC	Independent	Continuous	5 mins
Fusional reserve	Phoropter	Independent	Discrete	5 mins
Accommodation	Positive and negative relative accommodation	Independent	Continuous	5mins
Stereopsis	Randot stereoacuity test	Independent	Discrete	5 mins
Eye movement	NSUCCO Saccade	Independent	Discrete	1mins
	Pursuit	Independent	Discrete	1mins

Visual acuity and refractive errors were measured at near (0.4m) and far (6.0m) distances. For near acuity testing, Lea symbols were used for young children, while the logMAR chart was used for older children. The Early Treatment Diabetic Retinopathy Study (ETDRS) letter chart was also used to ensure consistency with the logMAR charting method (Huurneman and Boonstra, 2016). For distance vision, both logMAR and Lea symbols were used, as these methods are validated for accuracy in young children (Bailey and Jackson, 2016; Milling et al., 2015). Normal versus abnormal visual acuity was determined based on age-standardized reference intervals (Rosenfield and Logan, 2009).

To assess eye movements, the NSUCO Method was employed, which is cost-effective and requires no equipment. This method evaluates saccades and pursuits, essential components of eye movement. According to Maples (2003), "The NSUCO oculomotor test provides a standardized and efficient method to evaluate eye movements without the need for specialized equipment." Using the NSUCO Method, we could determine if participants had the fundamental visual skills necessary for performing the TVPS.

Eye alignment and binocular vision were assessed using cover testing for both near and far distances, while vergence function (convergence and divergence) was measured with the near-point of convergence (NPC) using the Royal Air Force (RAF) near-point rule (Mestre et al., 2018; Adler et al., 2007).

Fusional reserve was measured with the phoropter technique to determine the participants' ability to maintain a balance between convergence and divergence (Conway et al., 2012).

Accommodation was assessed using a phoropter, which is preferred over the RAF ruler. The phoropter measures positive and negative relative accommodation, observing how quickly a patient can stimulate (positive relative accommodation) or relax (negative relative accommodation) their accommodative ability.

Stereopsis was measured using the Randot stereoacuity test, which assesses two levels of stereopsis at 250 and 500 seconds of arc through graded (Wirt) circle and animal tests with stereo glasses (Kulp and Mitchell, 2005; O'Connor and Tidbury, 2018).

All equipment used for the optometric assessments was owned by the author, and it was ensured that all equipment was correctly calibrated and quality controlled before use.

2.4 Visual perception testing

The noted visual functions were correlated with participants' visual perceptive abilities, which were assessed using the TVPS 4th edition. This assessment is validated for use in children aged five years and older, making it suitable for the population group of interest (Brown and Peres, 2018). During the TVPS, subjects are shown several black and white stimuli and respond primarily through verbal communication, although gestures can also be used. Notably, the test does not rely on motor responses, unlike other visual perceptive tests (Martin, 2017).

The TVPS is based on two key theories: the Model of Visual Information Processing and the Cattell-Horn-Carroll Theory of Cognitive Abilities. The Model of Visual Information Processing posits that visual perception is influenced by three factors: visual integrity, visual efficiency, and visual information processing. The latter includes visual spatial, visuomotor, and analysis abilities (Scheiman, 2011). The TVPS measures visual analysis skills, providing information on discrimination, figure-ground perception, memory, and visual closure. It also incorporates the Cattell-Horn-Carroll Theory of Cognitive Abilities, suggesting that vision is influenced by both narrow and broad cognitive abilities. However, the TVPS only measures three of the 11 narrow cognitive functions: visualization, flexibility of closure, and memory (Brown and Peres, 2018). The test assesses seven distinct visual perceptual skills without requiring a motor response, ensuring that results reflect perceptual abilities rather than motor skills. Gardner (1996) mentioned that these seven skills are:

1) Visual Discrimination - The ability to identify differences and similarities in visual stimuli (Martin, 2006).
2) Visual Memory - The skill to recall visual information shortly after viewing it.

3) Spatial Relationships - The capacity to perceive spatial orientation and relationships between objects.
4) Form Constancy - Recognizing objects regardless of changes in size, shape, or orientation.
5) Sequential Memory - Recalling a sequence of visual elements in the correct order.
6) Figure-Ground Discrimination - Distinguishing an object from its background.
7) Visual Closure - Identifying a complete object from partial visual information.

The completion and scoring of the TVPS were guided by the published booklet. Each item presents 4-5 response options, with participants indicating their response verbally or through gestures. Correct responses score 1 point, and incorrect responses score 0. A ceiling score is reached for each component when participants make three consecutive incorrect responses. Scores are then tallied using the official scoring sheet to generate scaled scores and percentile ranks. Total standard scores, which are continuous and age-standardized, were used for statistical analysis. A standard score below 80 or a percentile rank below 25% indicates the presence of a visual perceptive problem (Brown and Peres, 2018). The TVPS demonstrates high reliability, making it suitable for repeated assessments in research and clinical practice. Consistent Test-Retest Reliability results are obtained when the test is administered on multiple occasions, indicating stability over time (Gardner, 1996). In terms of internal consistency, each subtest demonstrates a strong correlation with the overall score, reflecting the test's validity as a comprehensive measure of visual perception (Martin, 2006).

TVPS standardized the assessment of visual perception across participants and facilitated associative analysis with other optometric tests, including binocular vision, crucial for addressing the core research question. During analysis and interpretation of findings, the limitations in assessing various optometric parameters are acknowledged, adhering to best practices to minimize potential errors or biases. The TVPS required approximately 30-40 minutes per participant to complete independently of other optometric tests, allowing for efficient group testing of children. This approach ensured supervision by the investigator, facilitating accurate completion and addressing participant queries as needed (Brown and Peres, 2018). All seven perceptual domains of the TVPS (Table 2) were examined, consistent with prior studies exploring the interplay between visual perception and other visual functions (Gligorović et al., 2011; Ho et al., 2015; Ibrahimi et al., 2021).

To ensure participants' concentration, all were instructed to attempt completing the TVPS without interruption, with a break provided afterward and refreshments available. Children were encouraged to request a break if needed during the test. A pilot study of the TVPS was conducted with a subset of the sample to assess the feasibility of completing the assessment in one sitting within a small group format. This pilot revealed no issues; all children successfully completed the test and appreciated the subsequent break.

Table 2 Overview of the subtests of the TVPS (Martin, 2017).

Subtests	**Description**
Visual Discrimination (DIS)	Participants are asked to find the image in a field of five similar images that matches the presented target image
Visual Memory (MEM)	Participants are asked to remember a target image presented for five seconds in a field of four images
Spatial Relationships (SPA)	Participants are asked to find one image that is difference from others in a field of five images
Form Constancy (CON)	Participants are asked to find one image in a field of 4-5 images that matches the target image – the matching image is displayed in variant size, rotations and/or when embedded in a differing design
Sequential Memory (SEQ)	Participants are presented with an image in a sequence of elements for five seconds. They are then asked to remember it and find of the image with the same sequence on the next page
Visual Figure-Ground (FGR)	Participants are asked to find a target image embedded in a field of four variant and complex designs
Visual Closure (CLO)	Participants are asked to match an incomplete target image to a correct image in a field of four

2.5 Data analysis: Orange Workflow

This study employed several machine learning techniques available in Orange Data Mining software (version 3.35.0) to analyze the relationship between oculomotor functions and visual perception as measured by the TVPS-4. The Orange workflow used for the analysis is shown below (Figure 14). Note that, although gender differences have been reported for some components of the TVPS test, the sample size in this thesis was insufficient for a robust statistical analysis of TVPS subset scores by gender.

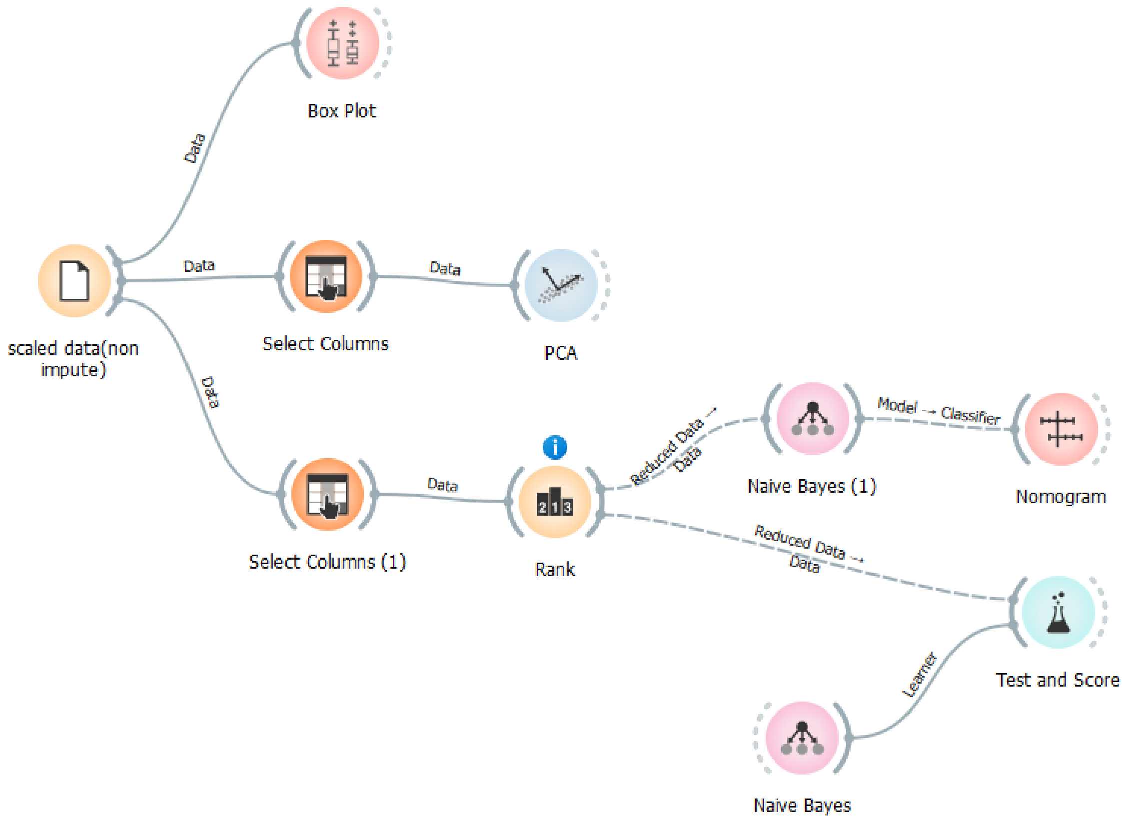


Figure 14 Orange workflow with interconnected widgets for analysis.

The machine learning techniques implemented include:

<u>Principal Component Analysis (PCA)</u>

PCA is an unsupervised machine learning technique commonly used for dimensionality reduction by identifying underlying factors that account for the maximum variance within a dataset. In this study, PCA was applied to investigate whether oculomotor functions and TVPS-4 scores could be consolidated into single principal components. However, the analysis revealed that the variance explained by a single principal component was insufficient to capture the complexity of the data. Consequently, alternative methods were employed to better address the research objectives.

Fast Correlation-Based Filter (FCBF)

FCBF is a feature selection technique designed to rank the importance of variables while eliminating those that are redundant. In this study, FCBF was employed to identify the most relevant oculomotor variables for predicting each parameter of the TVPS-4. By effectively streamlining the dataset, this method significantly reduced its complexity, enabling a more focused and efficient analysis.

Naïve Bayes Classification

Naïve Bayes Classification is a supervised machine learning model that operates under the assumption of independence among predictors, making it a straightforward and efficient tool for classification and predictive analysis. In this study, Naïve Bayes was utilized to model the relationships between selected oculomotor features and TVPS-4 parameters. This approach provided valuable insights into the direction and strength of these relationships, contributing to a deeper understanding of their underlying connections.

Nomogram Analysis

The Nomogram widget in Orange facilitated the interpretation of Naïve Bayes results, offering a visual representation of the influence of specific oculomotor functions on TVPS-4 scores.

Test and Score Evaluation

This assessed the reliability and performance of the machine learning models using metrics such as Area Under the Receiver Operating Characteristic Curve (AUROC), sensitivity, and specificity.

Orange provides a user-friendly platform with a visual workflow, making it highly accessible for researchers and eliminating the need for extensive coding expertise. This design enables seamless integration and interpretation of various machine learning techniques, allowing researchers to focus on analysis and insights rather than technical complexities. By applying advanced methods such as FCBF for feature selection and Naïve Bayes for predictive modeling, Orange offers capabilities that extend beyond the scope of traditional statistical tools like SPSS. Unlike SPSS, which is limited to basic statistical tests, Orange facilitates the discovery of complex, non-linear relationships between variables, offering deeper insights into multifaceted interactions. Its interactive features, such as generating nomograms for visualizing relationships, enhance data exploration and decision-making. These machine learning techniques are particularly suited for analyzing intricate connections, such as those between oculomotor functions and visual perception. By uncovering nuanced relationships and building robust predictive models, Orange Data Mining proves to be an ideal tool for this study, addressing limitations inherent in traditional statistical methods.

Data were uploaded using the ‘File widget’.

The 7 TVPS-4 visual perception scores were categorised as ‘High’ or ‘Low’, after applying a median split. These scores included Visual Discrimination (DIS), Visual Memory (MEM), Spatial Relationships (SPA), Form Constancy (CON), Sequential Memory (SEQ), Visual Figure-Ground (FGR), and Visual Closure (CLO).

The 18 oculomotor scores were categorised as follows:
*All categories of ‘High’ and ‘Low’ involved applying a median split. *

1. Pursuit (High, Low),
2. Saccades (Saccad - High, Low),
3. Distance positive relative vergence break (PRVb – High, Low),
4. Distance positive relative vergence recovery (PRVr – High, Low)
5. Near positive relative vergence break (PRVnb – High, Low),
6. Near positive relative vergence recovery (PRVnr – High, Low),
7. Positive relative accommodation (PRA – High, Low),
8. Distance phoria (PhoriaD – ESO, EXO, ORTHO),
9. Near phoria (PhoriaN – ESO, EXO, ORTHO),
10. Distance negative relative vergence break (NRVb – High, Low),
11. Distance negative relative vergence recovery (NRVr – High, Low),
12. Near point of convergence (NPC – ABOVE 5, BELOW 5, TTN),
13. Near cover test (NearCT – High, Low, ortho),
14. Stereopsis (Stereo – high, Low),
15. Negative relative accommodation (NRA – High, Low),
16. Near distance negative relative vergence break (NRVnr – High, Low),
17. Near distance negative relative vergence recovery (NRVnb – High, Low),
18. Age was also classified as ‘High’ (<8 years) or ‘Low’ (≥8 years) after a median split.

Chapter 3. Results and Discussion

3.1 Optometric Measures

In this study, there were 39 female participants and 58 male participants, with ages ranging from 6 to 14 years (mean age 8). Table 3 below gives the range, median and mean vales of all optometric parameters assessed.

In the assessment of eye movements, the NSUCO Method was utilized due to its cost-effectiveness and the absence of required specialized equipment. This approach evaluates saccades and pursuits, which are critical components of eye movement. Maples (2003) highlights the efficiency of the NSUCO oculomotor test, stating that it provides a standardized method for evaluating eye movements without the need for additional tools. By employing this method, we were able to determine whether participants possessed the foundational visual skills necessary to complete the TVPS.

Eye alignment and binocular vision were evaluated using cover testing at both near and far distances. Vergence function, including convergence and divergence, was assessed through the near-point of convergence (NPC) using the Royal Air Force (RAF) near-point rule (Mestre et al., 2018; Adler et al., 2007).

Visual acuity and refractive errors were assessed at both near (0.4m) and far (6.0m) distances. Near visual acuity was measured using Lea symbols for younger children and the logMAR chart for older children, ensuring age-appropriate methods. To maintain consistency with the logMAR charting approach, the Early Treatment Diabetic Retinopathy Study (ETDRS) letter chart was also employed (Huurneman and Boonstra, 2016). For distance vision, both the logMAR chart and Lea symbols were utilized, as these methods are validated for their accuracy in assessing young children's visual acuity (Bailey and Jackson, 2016; Milling et al., 2015). Normal and abnormal visual acuity were determined using age-standardized reference intervals (Rosenfield and Logan, 2009).

Accommodation was evaluated using a phoropter, which is considered more reliable than the RAF ruler for this purpose. The phoropter allows for the measurement of both positive and negative relative accommodation, assessing the patient’s ability to stimulate (positive relative accommodation, PRA) or relax (negative relative accommodation, NRA) their accommodative system.

Stereopsis was evaluated using the Randot stereoacuity test, which measures depth perception at varying levels of difficulty. This test uses graded Wirt circles and animal figures, viewed through stereo glasses, to assess stereoacuity at thresholds of 250 and 500 seconds of arc (Kulp and Mitchell, 2005; O'Connor and Tidbury, 2018).

Fusional reserve was assessed using the phoropter technique to evaluate participants' ability to balance convergence and divergence (Conway et al., 2012). These results provide a comprehensive overview of the participants' fusional reserve capabilities across both break and recovery points for convergence and divergence.

Table 3 Range, Mean, and Median of Optometric Parameters.

Optometric Parameters	Range		Mean	Median
	Min.	Max.		
Pursuit	6	18	13	13
Saccade	4	19	12.4	12
NPC	2 cm	25 cm	9.5cm	9 cm
Near Cover Test	7.22%	42.27%	24.92%	25.26%
Phoria Distance	0.5XOP	5.5XOP	2.63 XOP	Ortho
Phoria Near	10XOP	8XOP	5.38 XOP	Ortho
Refractive Errors	-0.50 Ds	-4.50 Ds	-2.25 Ds	-2.00 Ds
PRA	-6.00	1.50	-2.1	-2.25
NRA	0	3.75	2.00	2.00
Stereo	20 seconds of arc	600 seconds of arc	137.1 seconds of arc	40 seconds of arc
PRV Break	4	48	21.1	16
PRV Recovery	-12	18	6.3	4
PRV Near Break Point	4	40	20.7	18
PRV Near Recovery Point	-4	25	7.3	7
NRV Break	2	62	11.6	9
NRV Recovery	-8	14	2.8	2
NRV Near Recovery	-4	20	7	4
NRV Near Break	0	40	18.1	16

3.2 Visual Perception Measures with TVPS

The Test of Visual Perceptual Skills (TVPS) subtests were assessed to measure different aspects of visual perception among participants.

Visual Discrimination (DIS) was evaluated by asking participants to identify an image that matched a presented target from a set of five similar images. Scores ranged from 0 to 19, with a median of 9 and mean of 8.9 (Figure 15).

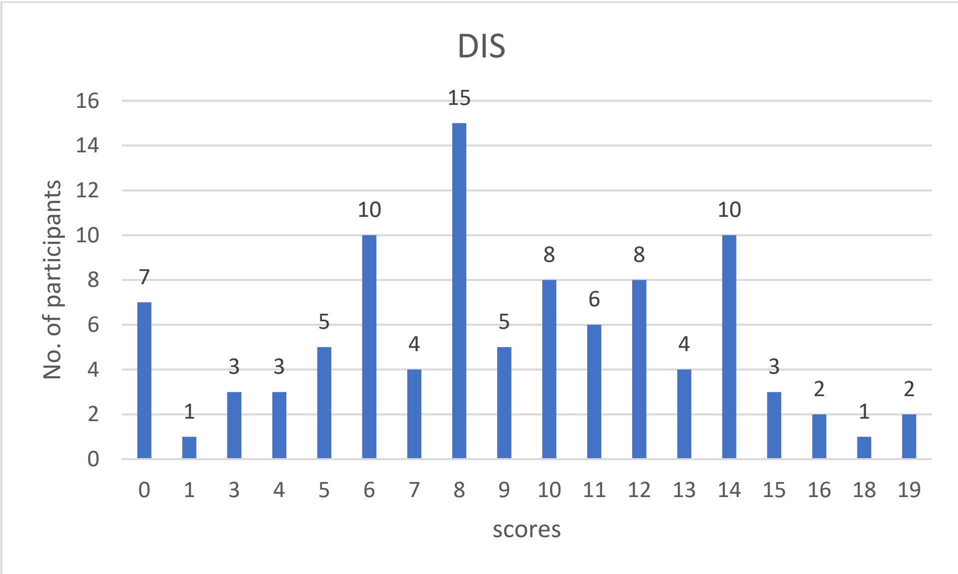


Figure 15 Distribution of Discrimination Scores of TVPS among Participants.

Visual Memory (MEM) required participants to memorize a target image presented for five seconds and then identify it from a set of four images. The scores ranged from 0 to 19, with a median of 7 and mean of 6 (Figure 16).

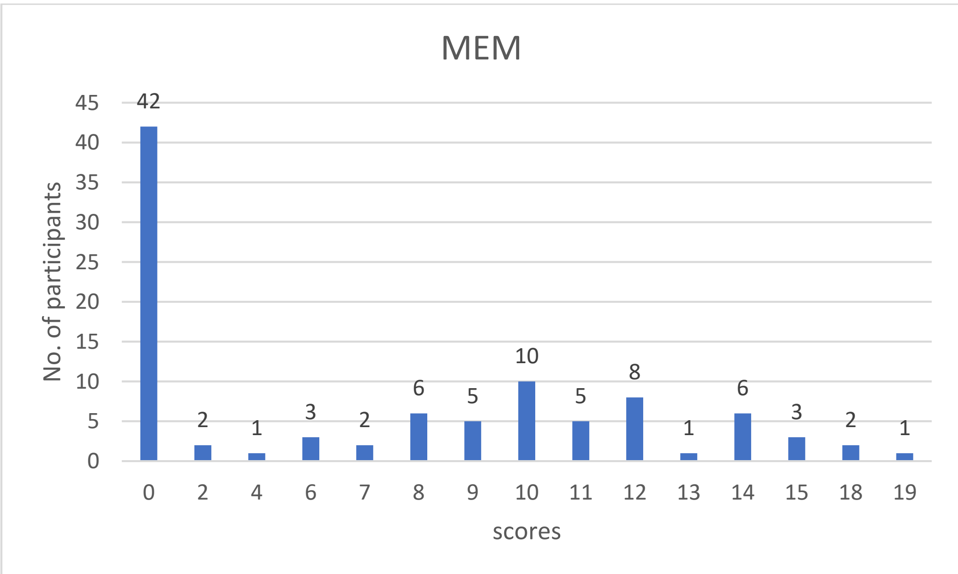


Figure 16 Distribution of Visual Memory Scores of TVPS among Participants.

Spatial Relationships (SPA) was assessed by asking participants to identify the one image that differed from the others in a set of five images. The scores ranged from 0 to 19, with a median of 10 and mean of 8 (Figure 17).

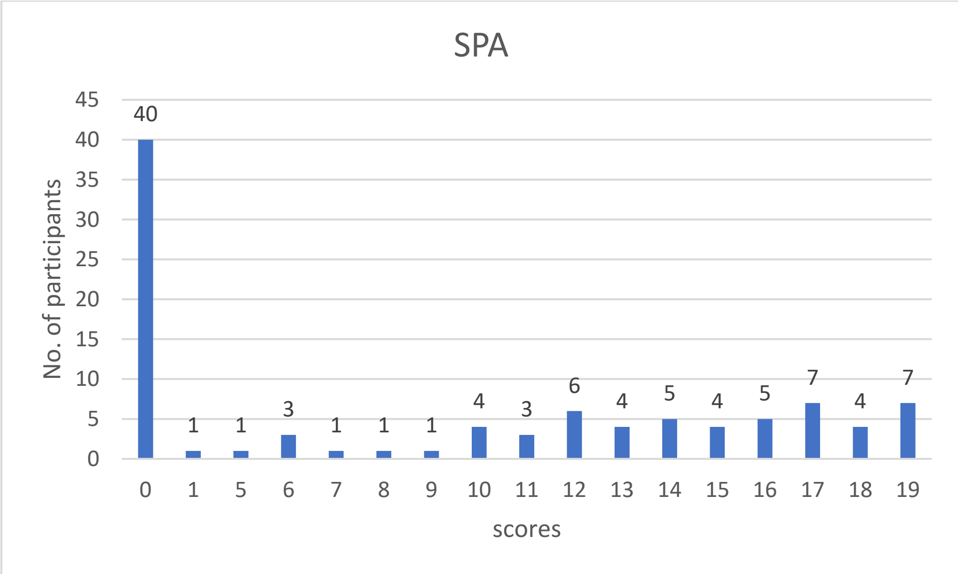


Figure 17 Distribution of Spatial Relationships Scores of TVPS among Participants.

Form Constancy (CON) involved identifying a target image from a set of 4–5 options, where the matching image could differ in size, rotation, or embedding within a different design. Scores ranged from 0 to 19, with a median of 5 and mean of 6 (Figure 18).

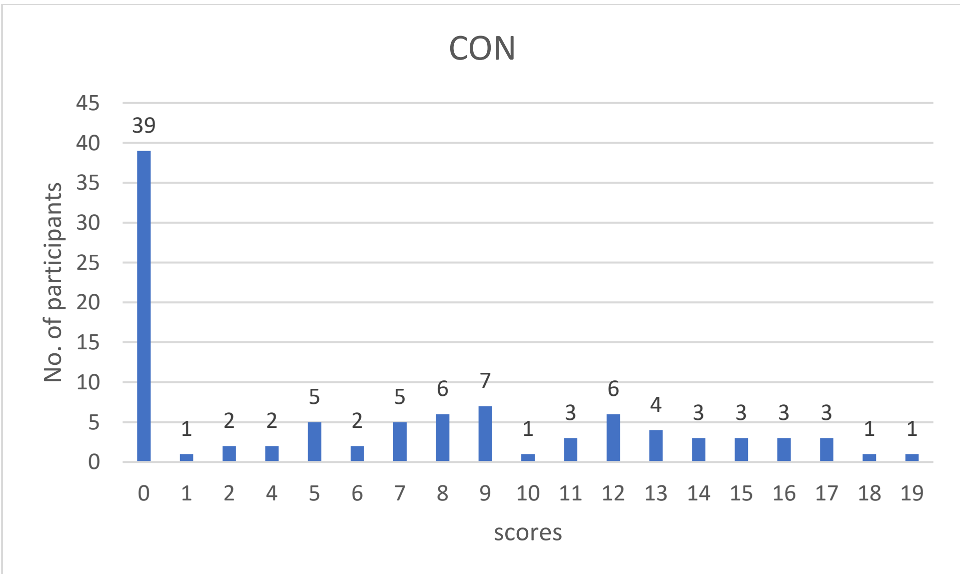


Figure 18 Distribution of Form Constancy Scores of TVPS among Participants.

Sequential Memory (SEQ) was tested by showing participants an image containing a sequence of elements for five seconds, after which they were asked to recall the sequence and identify the correct image on the following page. Scores ranged from 0 to 15, with a median of 2 and mean of 5.1 (Figure 19).

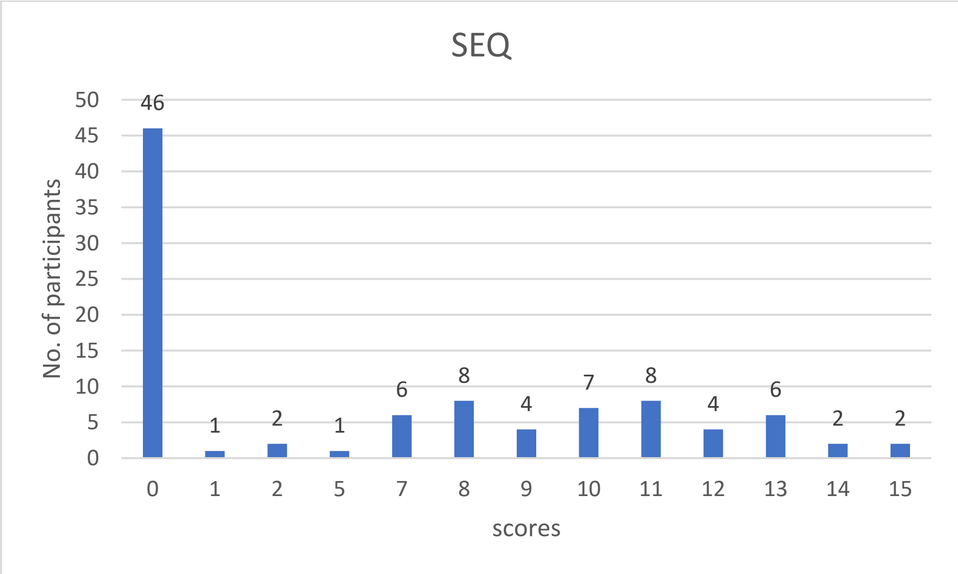


Figure 19 Distribution of Sequential Memory Scores of TVPS among Participants.

Visual Figure-Ground (FGR) required participants to locate a target image embedded within a complex visual field containing four varying designs. Scores ranged from 0 to 19, with a median of 9 and mean of 9.2 (Figure 20).

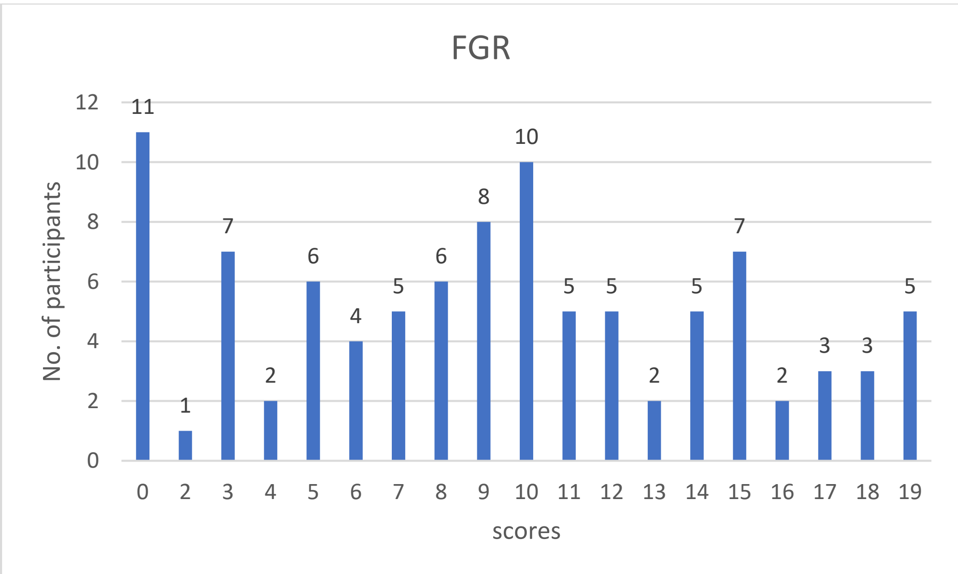


Figure 20 Distribution of Visual Figure-Ground Scores of TVPS among Participants.

Visual Closure (CLO) was assessed by asking participants to match an incomplete target image with its correct counterpart from a set of four options. The scores ranged from 0 to 19, with a median of 9 and mean of 8.9 (Figure 21).

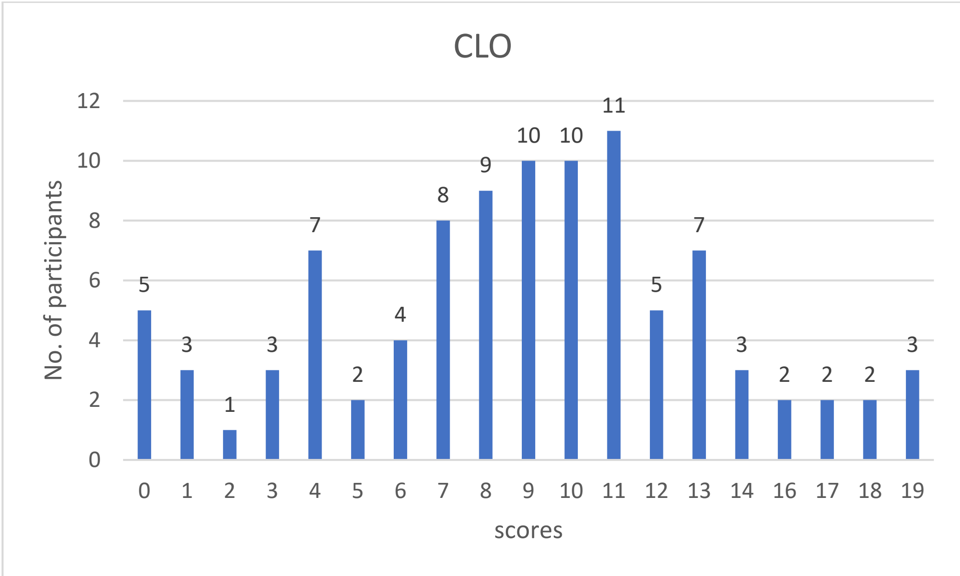


Figure 21 Distribution of Visual Closure Scores of TVPS among Participants.

3.3 Box plot

The Box plot widget allowed preliminary analysis of associations between all variables, using univariate Chi-square tests. An example output is shown below (Figure 22).

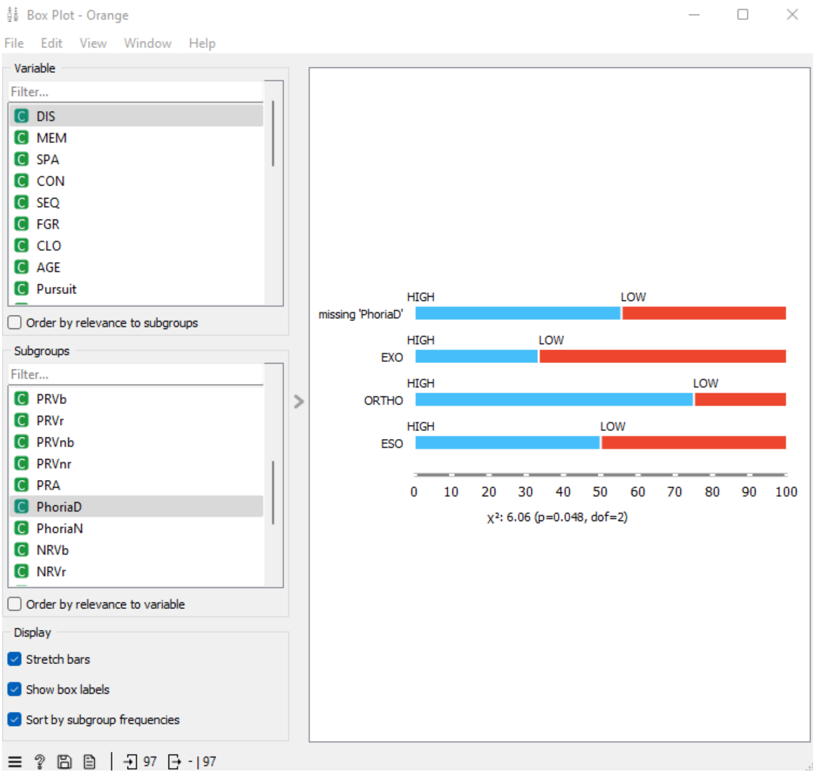


Figure 22 Example output of the Orange Box Plot widget. The association between the DIS (highlighted in the Variable list) and PhoriaD (highlighted in the Subgroups list) is explored. The display is set to Stretch bars so that the relative proportions of subgroup are revealed. Bars show that the proportion of LOW DIS scores found in EXO PhoriaD subgroup is greater than is found in the ESO or ORTHO subgroups. Since, the data is non-imputed, therefore the missing "PhoriaD" subgroup was shown in the results. A chi-square test also shows that this finding is statistically significant (Chi-square = 6.06, df = 2, p = 0.048).

Table 4 shows if the associations explored between all 25 variables were statistically significant (in which case the p-value is shown and in red) or not (in which case N is shown).

Table 4 Exploration of associations between all 25 variables using the Orange Box Plot widget. Statistically significant (p < 0.05) associations are in red and also show the p-value; otherwise, N is shown.

	DIS	MEM	SPA	CON	SEQ	FGR	CLO	AGE	Pursuit	Saccad	PRVb	PRVr	PRVnb	PRVnr	PRA	PhoriaD	PhoriaN	NRVb	NRVr	NPC	NearCT	Stereo	NRA	NRVnr	NRVnb
DIS		0.002	N	0.001	0.002	N	0.019	N	N	N	N	N	N	N	N	0.048	0.016	N	N	N	N	N	N	N	N
MEM			N	N	N	0.033	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	0.032	N	N
SPA				N	N	0.010	N	N	N	N	N	N	N	N	0.001	N	N	N	N	0.009	N	N	N	N	N
CON					N	N	N	N	N	N	N	N	N	N	0.003	N	0.030	N	N	N	0.002	N	N	N	N
SEQ						N	N	N	N	N	N	N	N	N	0.001	N	N	N	N	0.035	N	0.029	0.008	N	N
FGR							0.016	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	0.046	N
CLO								N	N	N	N	N	N	N	N	N	N	N	N	N	0.029	0.001	N	N	N
AGE									N	N	0.005	0.016	N	0.028	N	0.009	0.047	N	N	N	N	N	N	N	N
Pursuit										N	0.007	N	0.026	N	0.046	0.009	N	N	N	N	N	N	N	N	N
Saccad											0.026	N	N	N	0.032	N	N	N	N	N	N	N	N	N	N
PRVb												N	N	N	N	N	N	N	N	N	N	N	N	N	0.001
PRVr													0.007	0.001	N	N	N	N	N	N	N	N	N	N	0.001
PRVnb														N	N	N	N	N	N	N	N	N	N	N	0.011
PRVnr															N	N	N	N	N	N	N	0.026	N	0.017	0.001
PRA																0.012	N	N	N	N	N	N	N	N	N
PhoriaD																	0.006	N	N	N	N	N	N	N	N
PhoriaN																		N	N	N	N	N	N	N	N
NRVb																			N	N	N	N	N	N	N
NRVr																				N	N	N	N	N	N
NPC																					N	N	N	0.015	N
NearCT																						0.050	N	N	N
Stereo																							N	N	N
NRA																								N	N
NRVnr																									0.002
NRVnb																									

The findings of Table 4 are only indicative as (a) the presence of a statistically significant association can be influenced by untested interactions between variables and (b) a total of 300 associations tested at a critical p-value of 0.05 are prone to spurious statistically significant findings. Bonferroni correction (Armstrong, 2014) of 0.0002 (the critical p-value of 0.05 divided by 300 tested associations) was applied and revealed no statistically significant associations between TVPS-4 and oculomotor scores. On the other hand, statistically significant associations remain between all the 7 TVPS-4 scores and 13 of the 18 (inc age) oculomotor scores (except age, pursuit, saccadic, NRVb, NRVr).

The associations revealed within TVPS-4 and oculomotor scores suggest that they may be combined into single aggregate scores; one for TVPS-4, and another oculomotor function. This was explored using principal components analysis (PCA).

3.4 PCA

Principal components analysis (PCA) (Chan, 2004) is a form of unsupervised machine learning, meaning it operates without a target or dependent variable. The goal of PCA is to identify underlying groups, known as principal components, within a set of variables. In this study, the objective was to determine whether a single principal component, derived from multiple features (independent variables), could explain at least 80% of the total variance—known as the 80% rule (Chan, 2004). If successful, this component could provide a single aggregate score for both TVPS-4 and oculomotor function, effectively reducing the data to a more manageable form.

This exploration was carried out by selecting the features of interest, using the Select Columns (1) widget, before passing them to the PCA widget (see Figure 14). Figure 23 shows how the Select Columns (1) widget was set up for (a) the 7 TVPS-4 features, and (b) the 18 oculomotor features. Note that no target variable was assigned for this unsupervised machine learning task.

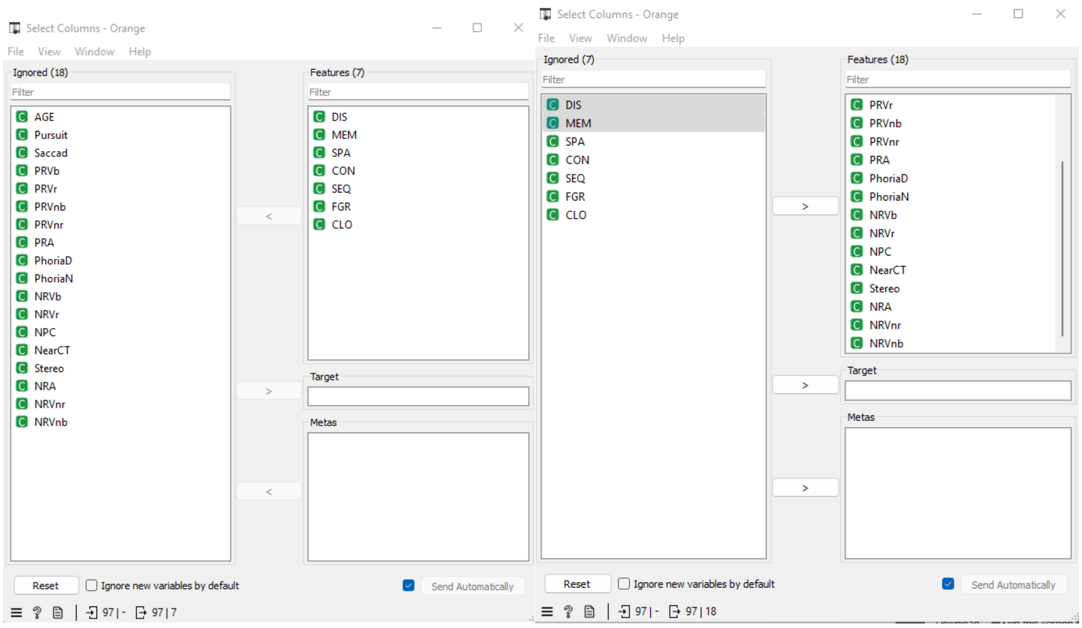
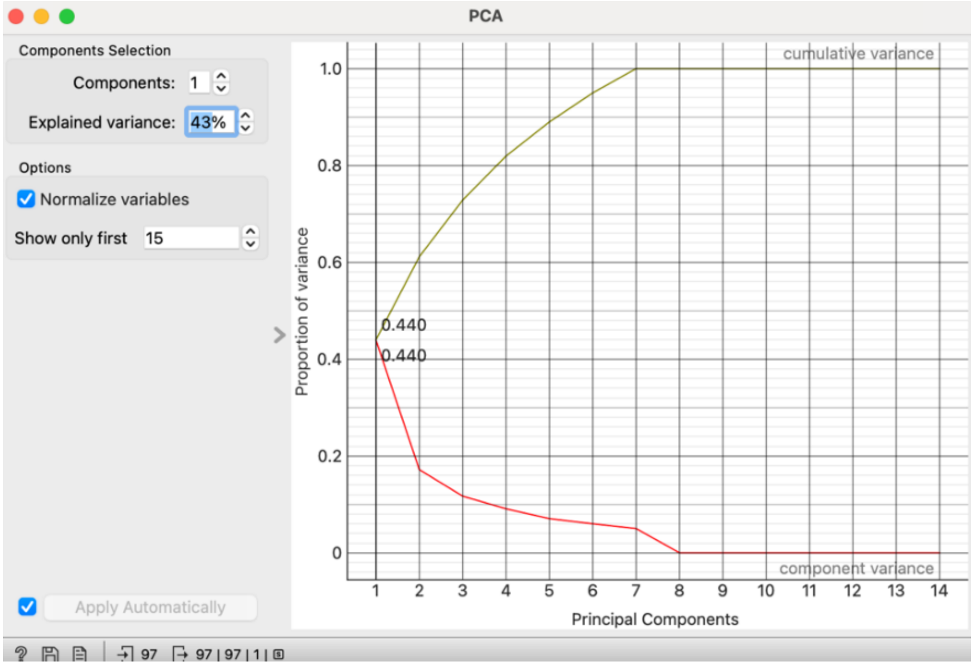


Figure 23 Setting up the Orange Select Columns (1) widget (see Figure 14) for (a) the 7 TVPS-4 features (box to the left) and (b) the 18 oculomotor features.

Figure 24 presents the PCA results. The analysis revealed that a single principal component accounted for only 43% of the variance across the seven TVPS-4 features and 17% of the variance across the 18 oculomotor features. These values are significantly lower than the 80% threshold required by the 80% rule. As a result, a single principal component could not be used as an aggregate score for either TVPS-4 or oculomotor function.



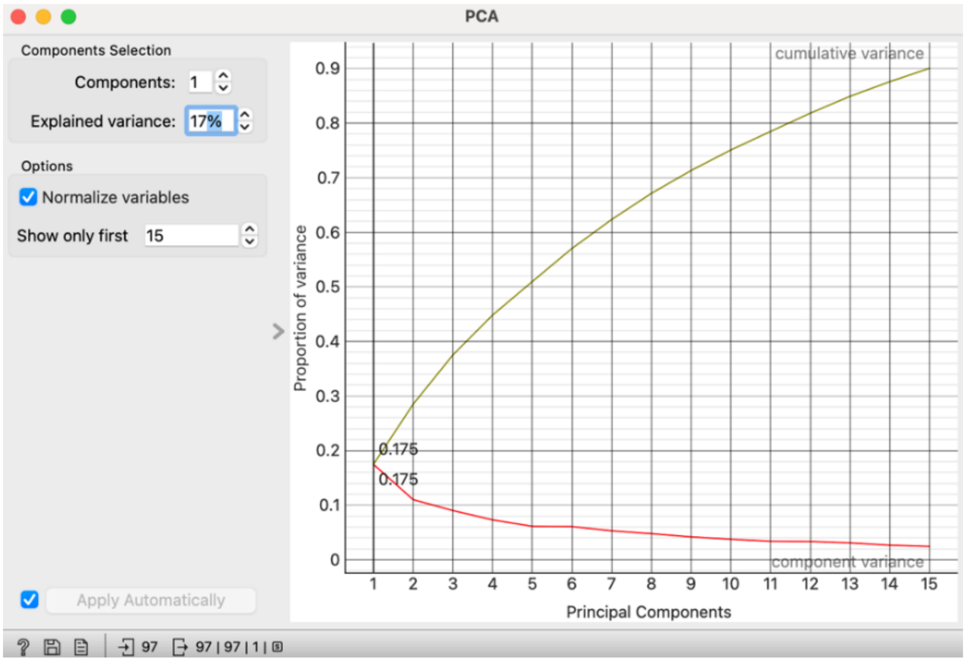


Figure 24 Principal components analysis (PCA) shows that the variance accounted for by a single principal component is (a) 43% for TVPS-4 and (b) 17% for oculomotor functions.

This phase of the study was discontinued, and an alternative method for data reduction was explored (see next section). However, before moving on from PCA, it is worth noting that number principal components were needed to account for 80% of the variance in (a) 4 for TVPS-4 features, and (b) 12 components for oculomotor features (inc age). This suggests that both TVPS-4 and oculomotor measures reflect a smaller set of underlying factors (principal components).

3.5 Rank Table

After ruling out PCA as a data reduction method in Section 3.4, it became evident that the seven TVPS-4 parameters would need to be analyzed as separate dependent variables. The next step was to determine whether the 18 oculomotor features (independent variables) could be reduced in some way. The Orange Rank widget was used for this purpose, offering seven different methods to rank independent variables based on their relative importance to a specified dependent variable. Among these, the Fast Correlation Based Filter (FCBF) was deemed the most efficient (Yu & Liu, 2003), as it was the only method that eliminated redundant independent variables. By applying FCBF, it became possible to identify which of the 18 oculomotor features had an impact on each of the seven TVPS-4 parameters. This phase of the study provided valuable insights into the relationship between oculomotor functions, as measured by optometrists, and visual perception as assessed by TVPS-4.

In this part of the study, features of interest were selected using the Select Columns widget before being processed through the Rank widget (see Figure 14). Figure 25 provides an example of how the Select Columns widget was configured and the corresponding output from the Rank widget. In this case, the Select Columns widget was used to designate DIS (the first TVPS-4 parameter) as the target (dependent variable), while the 18 oculomotor functions, along with age, were set as the independent variables. The Rank widget then applied the FCBF method, revealing that only “PhoriaN” and “Stereo” had an influence on DIS.

This finding aligns with the statistically significant associations between DIS, “PhoriaN” and “PhoriaD” observed in Table 4. Interestingly, no association was found between DIS and “PhoriaD”. Thus, DIS is influenced by only two of the 18 features: PhoriaN and Stereo. This not only represents a substantial reduction in the number of candidate independent variables but also provides new insights into which specific oculomotor functions affect this TVPS-4 parameter.

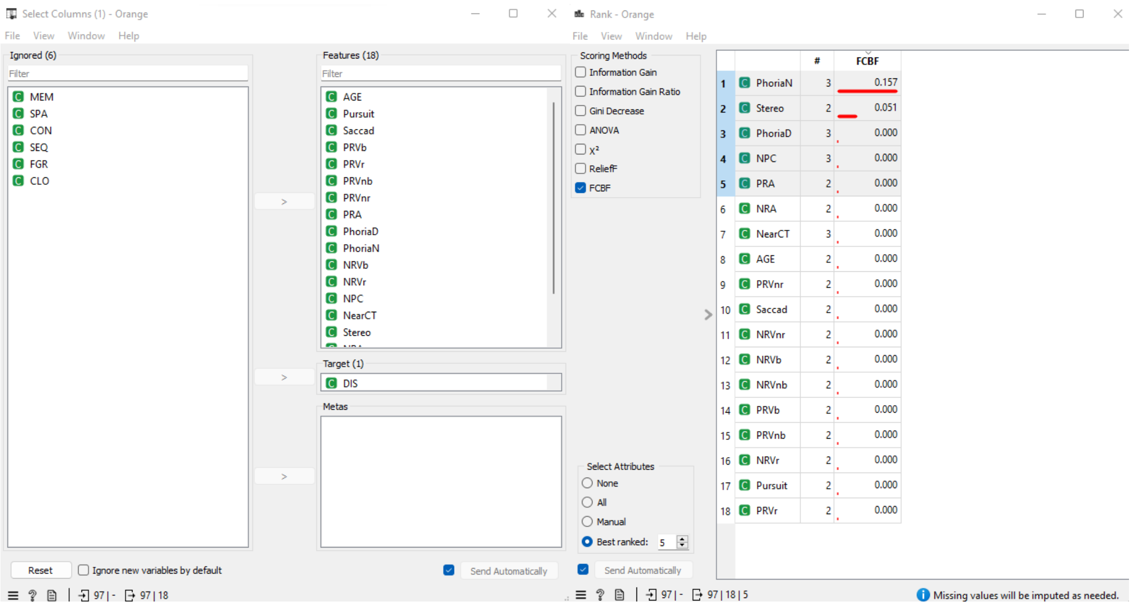


Figure 25 Example showing how Orange's (a) Select Columns is set up, and (b) the Rank widget output.

The analysis shown in Figure 25 was extended to all seven TVPS-4 parameters, with the findings summarized in Table 5. In this table, age and the 17 oculomotor features are listed in rows, while the seven TVPS-4 parameters are displayed in columns. The numbers in each cell represent the ranking, with 1 being the highest. Age had minimal influence out of all the seven TVPS-4 parameter. The analysis also revealed that six oculomotor features — AGE, Pursuit, PRVb, PRVr, PRVnb, NRVb — were redundant, as shown in Table 5. Notably, the 17 oculomotor influences identified for the various TVPS-4 parameters in Table 5 are consistent with the oculomotor associations observed in Table 4.

Table 5 Summarised outcome of FCBF showing the oculomotor features (rows) that influence each of the 7 TVPS-4 parameters (columns). The numbers represent ranks (1 = highest rank).

	DIS	MEM	SPA	CON	SEQ	FGR	CLO
AGE							
Pursuit							
Saccades						2	
PRVb							
PRVr							
PRVnb							
PRVnr							5
PRA	5	1	1	1	1		
PhoriaD	3	4	4			4	
PhoriaN	1	5	2	2	5		
NRVb							
NRVr						5	
NPC	4		3		3	3	3
NearCT		2		3			4
Stereo	2			5	2		1
NRA		3	5	4	4		
NRVnr						1	
NRVnb							2

3.6 Naïve Bayes and Nomogram

Naïve Bayes is the simplest form of supervised machine learning available in Orange, yet it is recognized for its strong performance (Zhang, 2004). Supervised machine learning requires a target variable, and in this study, each of the seven TVPS-4 parameters serves as the target (or dependent variable). The Naïve Bayes widget takes a multivariate approach, allowing the simultaneous analysis of multiple oculomotor functions (the independent variables) and their influence on a specific TVPS-4 parameter, while accounting for confounding factors.

The term "naïve" refers to the assumption that the oculomotor functions are not inter-correlated. This assumption is valid in this study because FCBF was used to select the oculomotor functions for each analysis (see Section 3.5). Additionally, the Rank widget, which performs the FCBF, passes the data directly to the Naïve Bayes widget (see the workflow in Figure 14). While Orange offers other, more complex supervised machine learning options, Naïve Bayes was chosen for its simplicity, making it accessible for optometrists engaged in practice-based research who may lack the time or training to use more advanced methods.

The Nomogram widget enhances the interpretability of Naïve Bayes outputs, offering "white box" advantages. In contrast, some machine learning methods possess "black box" disadvantages, where the rationale behind their decisions is not transparent (Tan et al., 2021). In Orange, only Naïve Bayes and logistic regression can be connected to the Nomogram widget; however, logistic regression is not as straightforward as Naïve Bayes.

Decision tree analysis is another supervised machine learning method with "white box" advantages, as its results can be visualized using the Tree Viewer widget. However, similar to logistic regression, decision tree analysis lacks the simplicity of Naïve Bayes.

In this part of the study, the direction of influence on all 7 TVPS-4 parameters of the oculomotor functions, selected using FCBF (see Table 5), was explored using Naïve Bayes supervised machine learning, exploiting the 'white box' advantages of the Nomogram widget. Figure 26 shows an example nomogram and the findings for all 7 TVPS-4 parameters are summarised in Table 6.

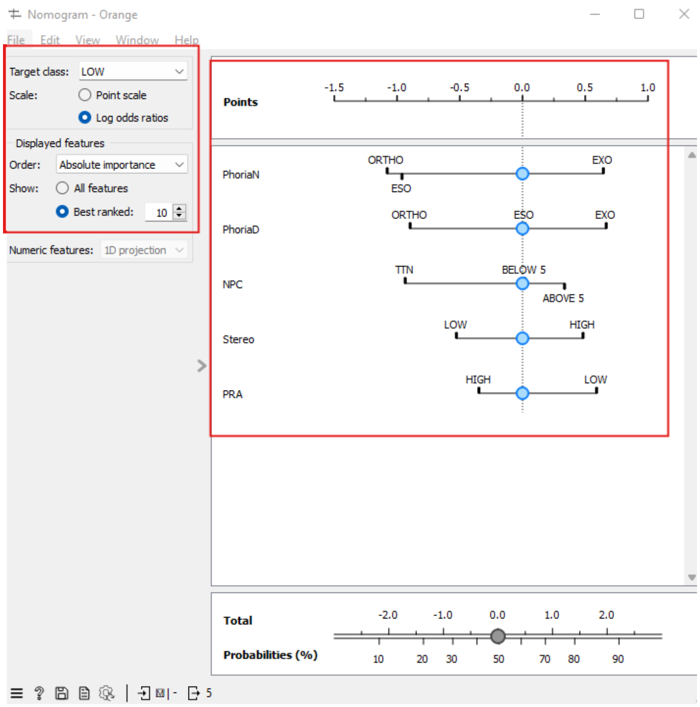


Figure 26 Example showing how Orange's Nomogram widget can be used to discover the direction of influence of oculomotor outcomes on a specified TVPS-4 parameter. The nomogram eases interpretation of output from the Naïve Bayes widget; offering 'white box' advantages. Here, the nomogram has been set to show how the TVPS-4 DIS scores are influenced by oculomotor PhoriaD and other oculomotor functions outcomes selected using FCBF (see Table 2). The nomogram reveals that people with EXO for PhoriaN, ESO for PhoriaD, NPC above 5, High Stereo and Low PRA tend to have LOW TVPS-4 DIS scores.

The nomogram shown in Figure 26 contains more detail than is necessary for the purposes of this study. Relevant sections of the nomogram are highlighted in red rectangles. These areas illustrate how the oculomotor functions, selected using FCBF, influence LOW TVPS-4 DIS scores. The nomogram is also configured to rank the oculomotor functions by Absolute Importance.

The main display, located within the largest rectangle, indicates the directions of influence. Here, we observe that “PhoriaN” has the greatest influence, followed by “PRA”, which has the least influence; this is reflected by its position in the display and the width of the horizontal bar representing its absolute importance. The blue circles on the horizontal bars indicate a null point, where the probability of a LOW DIS score is no greater than its prevalence in the dataset. However, the probability increases for individuals with EXO for PhoriaN, ESO for PhoriaD, NPC Below5, High Stereo and High PRA.

Interestingly, further examination of the findings from the Box Plot widget (summarised in Table 4) reveals that they agree with the directions of influence shown in the nomogram (Figure 26). However, it is important to note that the univariate analyses conducted with the Box Plot widget are susceptible to confounding factors. In contrast, the multivariate analyses presented in the nomogram account for these confounding effects, making them more reliable.

Table 6 Summarised outcomes of Naïve Bayes supervised machine learning after FCBF feature selection (see Table 5), extracted from the Nomogram widget, showing the directions of influence of oculomotor features (rows) in relation to LOW scores for the 7 TVPS-4 parameters (columns). The numbers in red brackets represent ranks (1 = highest rank) of influence, according to Naïve Bayes from the Nomogram widget. Numbers unbracketed were Naïve Bayes ranks from the FCBF ranks (shown in Table 2). Similar ranks between Nomogram and FCBF for the 7 TVPS-4 parameters were only 2-3 out of 7 TVPS skills.

Direction of influence: towards LOW

	DIS	MEM	SPA	CON	SEQ	FGR	CLO
AGE							
Pursuit							
Saccades						2(5)HIGH	
PRVb							
PRVr							
PRVnb							
PRVnr							5(3)LOW
PRA	5 HIGH	1 HIGH	1(2)HIGH	1(3)HIGH	1HIGH		
PhoriaD	3 (2) ESO	4(2) EXO	4EXO			4(3)ESO	
PhoriaN	1 EXO	5EXO	2(1)ESO	2(1)ESO	5(3)ESO		
NRVb							
NRVr						5(4)HIGH	
NPC	4 (3) BLW 5		3ABV5		3(4)ABV5	3(1) ABV5	3(4)BLW 5
NearCT		2 (4) ORTHO		3(2)EQUAL			4(2)ORTHO
Stereo	2 (4) HIGH			5HIGH	2(5) HIGH		1 HIGH
NRA		3 HIGH	5HIGH	4 HIGH	4(2) HIGH		
NRVnr						1(2) HIGH	
NRVnb							2(5)LOW

Table 6 provides additional insights into the directions of influence that oculomotor functions have on each of the seven TVPS-4 parameters, following the example analysis presented in Figure 26. Consistent directions of influence indicate that HIGH Stereo, HIGH NRA, and HIGH PRA oculomotor outcomes consistently lead to LOW scores on five out of the seven TVPS-4 parameters. In contrast, the directions of influence for the PhoriaD, PhoriaN, NPC and Near CT oculomotor functions show inconsistencies. Unbracketed numbers reveal where influence ranks differed, according to Naïve Bayes machine learning and FCBF feature selection. These differences may have arisen because FCBF feature selection is independent of any particular machine learning method.

The reliability of the Naïve Bayes supervised machine learning model is a crucial aspect of this study. Understanding its effectiveness and performance is essential for evaluating the validity of the findings. The following section provides an in-depth analysis of the model's reliability.

3.7 Test and Score

Machine learning performance is an indicator of reliability and can be expressed as the Area Under the Receiver Operating Characteristic curve (AUROC), sensitivity, and specificity (Lu et al., 2018). Orange's Test and Score widget provides these measures. Figure 27 shows an example of the Test and Score widget output and Table 7 provides a summary of the findings for all 7 TVPS-4 parameters.

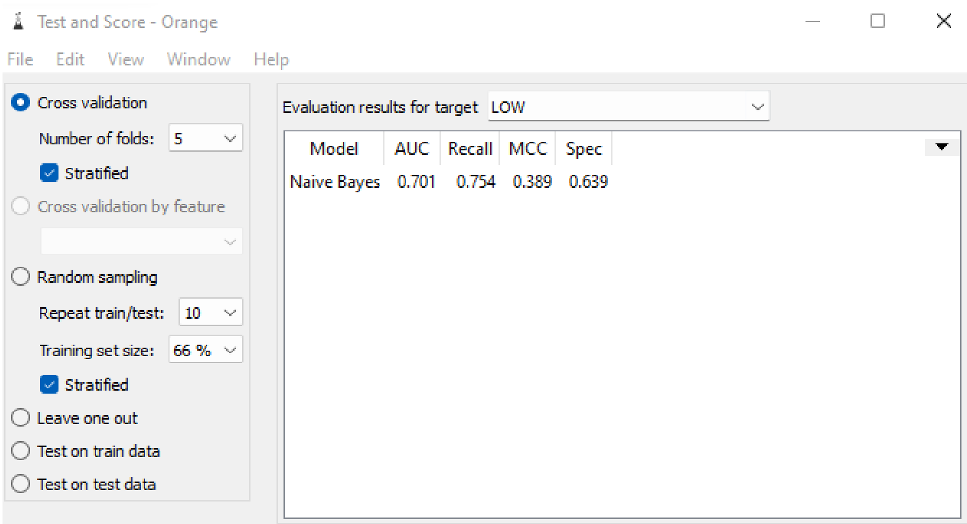


Figure 27 Example showing how Orange's Test and Score widget is used to determine the reliability (performance) of Naïve Bayes machine learning models. Stratified 5-fold cross validation is used to provide the most realistic estimate of model performance. Here, the widget has been set to show how well the model detects LOW TVPS-4 MEM scores, the model has an AUROC of 0.701, sensitivity of 0.754 (shown as Recall) and specificity of 0.639. Informedness (sensitivity + specificity – 1) is 0.393 i.e., 39% above chance. As such this is not a reliable model.

Table 7 AUROC, Sensitivity, Specificity and Informedness for the 7 models created to predict LOW TVPS-4 scores from oculomotor functions (see Table 6).

	DIS	MEM	SPA	CON	SEQ	FGR	CLO
AUROC	0.706	0.701	0.720	0.742	0.768	0.634	0.735
Sensitivity/Recall	0.729	0.754	0.769	0.871	0.809	0.500	0.619
Specificity	0.449	0.639	0.469	0.400	0.517	0.660	0.745
MCC	0.185	0.389	0.242	0.311	0.329	0.161	0.367
Informedness	0.178	0.393	0.238	0.271	0.326	0.160	0.364

Stratified 5-fold cross-validation was employed (see Figure 27) to provide a realistic estimate of model performance, serving as an indicator of reliability. Cross-validation assesses how well a model generalizes to new data, whereas failing to use it can result in an overfitted model that only performs well on the dataset used for training (Demšar & Zupan, 2021; Lu et al., 2018). Table 7 presents the AUROC, sensitivity, specificity, and informedness for the seven models developed to predict LOW TVPS-4 scores based on oculomotor functions. According to D'Agostino et al. (2013), an AUROC below 0.7 is considered suboptimal, between 0.7 and 0.8 is good, and above 0.8 is excellent. All of the 7 TVPS skills, that which predicts scores, may be considered to be fairly reliable; it actually had an good performance (AUROC 0.7 to 0.8). Informedness combines sensitivity and specificity to indicate model performance above chance (Powers, 2011). Even the most reliable MEM model only performed 39 % above chance. These findings are not surprising given the limited sample size.

A summary of the findings from this study can be found in Tables 8-11:

Table 8 Summary of Key Findings.

TVPS Domain	Percentage Scoring Below 25%	Associated Visual Functions Impacted	Predictive Optometric Factors
Visual Discrimination	33-57%	Form Constancy, Visual Memory	Phoria (near/far), NPC
Spatial Relationships	33-57%	Visual Memory, Accommodation	Vergence, Age
Sequential Memory	33-57%	Form Constancy, Stereopsis	Accommodation, Vergence
Figure Ground	33-57%	Visual Closure, Stereopsis	Vergence, Pursuits, Saccades
Visual Closure	33-57%	Accommodation, Age	Pursuits, Saccades, Vergence

Table 9 PCA and Machine Learning Results.

Component	Variance Explained (%)	Optometric Variables (Count)	TVPS Domains (Count)
PCA	78-82.7%	12	4
FCBF	-	Multiple	Multiple
Naive Bayes	-	Multiple	Limited Reliability

Table 10 Significant Associations (Summary).

Optometric Function	TVPS Domain Affected	Type of Association
Phoria (Near/Far)	Visual Discrimination, Spatial Relationships	Negative
Positive Relative Accommodation	Visual Memory, Form Constancy	Negative
Vergence Function	Spatial Relationships, Visual Closure	Negative
Near Point of Convergence	Multiple TVPS Domains	Negative
Stereopsis	Figure Ground, Visual Closure	Negative

Table 11 Evaluation of Machine Learning Performance.

Metric	Range for Non-Impute Data	Interpretation
Predictive Accuracy	0.617-0.806	Moderate Accuracy
Sensitivity	0.447-0.714	Prone to Under-Predicting
Specificity	0.571-0.851	Over-Predicting Associations
Informedness	0.221-0.458	Low Informedness
MCC	0.136-0.427	Limited Reliability

Chapter 4. General Discussion

4.1 Summary

This research aimed to investigate the relationship between visual perception and binocular vision in school children aged 6 to 14 years. Descriptive statistics indicated that a significant portion of the participants had previously undetected optometric abnormalities, along with impairments in visual perception and binocular vision. This finding was unexpected, given the reasonably sized sample of 97 children who completed the optometric assessments.

Notably, between 33% and 57% of the children scored below 25% in each of the domains of the Test of Visual Perceptual Skills (TVPS), indicating difficulties in visual discrimination, form constancy, visual memory, sequential memory, figure-ground perception, spatial relationships, and visual closure.

Importantly, several significant associations emerged across the analyses conducted. The most influential factors affecting TVPS scores included phoria at near and far distances 14.34%; n=14/97, positive relative accommodation 11.34%; n=11/97, stereopsis 9.28%; n=9/97, near point of convergence 8.25%; n=8/97, near cover testing 8.25%; n=8/97, and age 8.25%; n=8/97. The key findings of this study are discussed in relation to existing literature in the following subsection.

Estimation of the size effect involved determining Matthews correlation coefficient (MCC) for the Naïve Bayes models that were trained to predict Matthews correlation coefficient is particularly useful for the binary classifications carried out in this study.

MCC is a balanced measure used for evaluating the quality of binary (two-class) classifications. It takes into account true positives, true negatives, false positives, and false negatives, offering a more comprehensive evaluation compared to simpler metrics like accuracy.

The highest MCC value (0.389) was observed for Visual Memory (MEM), indicating the model performed best in this domain. The lowest MCC value (0.161) was for Visual Figure-Ground (FGR), showing weaker classification reliability for this domain.

It approximates Pearson's correlation coefficient for the classification of supervised machine learning methods, thereby providing an estimate of effect size in which values of 0.1, 0.3 and 0.5 represent, respectively, small, medium and large effects.

4.2 Evaluation of Findings

4.2.1 Correlation with the Wider Literature

The findings of this study reveal both previously supported and novel associations between visual perception, binocular vision, and other optometric functions in school-aged children, analyzed using Orange machine learning software. The research consistently demonstrated that impairments in binocular vision—evidenced by abnormal assessment results in accommodation, convergence, phoria, fusional vergence, and stereoacuity—were significantly linked to decreased visual perception, as indicated by low scores in the Test of Visual Perceptual Skills (TVPS). Since these measures are accepted indicators of binocular vision, it can be concluded that impairments in this area negatively affect visual perception (Eperjesi and Rundstrom, 2001). This includes functions such as visual discrimination, visual memory, spatial relationships, visual closure, figure-ground perception, and form constancy. However, few connections were found with sequential memory.

In the TVPS, sequential memory requires respondents to identify a unique sequence of shapes among similar combinations, with one containing the target sequence. Variations in test performance by age could explain these findings; since this task resembles a "spot the similarity" scenario, subjects might have been more familiar with it and performed better than on other perceptual functions (Martin, 2017). This could result from prior practice or indicate that the test's difficulty is not appropriately tailored to the age of the subjects, possibly making it too easy. Therefore, it may be necessary for the developers of the TVPS to reassess this aspect of the assessment.

The influence of age was confirmed in the FCBF rank test, which showed a significant association between age and abilities in visual memory and visual closure. Age emerged as a consistent and important factor across all analyses (Chi-Squared, FCBF, and Naïve Bayes), indicating that the median split (<8 years versus ≥8 years) effectively revealed this mediating factor. Specifically, younger children tended to score lower in visual memory and visual closure.

Participants in this study achieved a mean score of 4.8 for sequential memory, with 38.2% scoring below the 25th percentile. This suggests that the test identified significant issues in perceptual function for this particular task. Consequently, it may imply that while impairments in binocular vision do not appear to affect sequential memory, this conclusion might be surprising from an optometric standpoint. It is possible that cognitive memory has a greater influence on sequential memory testing, which could complicate the interpretation of this TVPS domain.

Despite previous findings, the FCBF rank test indicated that the primary factors influencing sequential memory were accommodation, near point of convergence, and stereoacuity. These results conflict with the associational analysis, suggesting that impairments in binocular vision negatively impact sequential memory.

Phoria, a misalignment of the eyes that often occurs due to fatigue (Eperjesi and Rundstrom, 2001), may contribute to this issue. Since parts of the TVPS require sustained concentration and visual attention, eye muscle fatigue, especially in the latter sections of the test, could lead to phoria in some participants, resulting in poorer scores in various TVPS domains.

This may also explain suboptimal performance in other areas, such as visual discrimination and figure-ground perception, which were significant in the associational analysis. Notably, phoria at distance significantly affected visual discrimination, figure-ground perception, and visual memory, underscoring the interconnectedness of binocular vision and visual perception.

This research suggests that the type of phoria may differentially impact visual perception abilities. The FCBF and Naïve Bayes machine learning analyses revealed that exophoria had more adverse effects on TVPS domains compared to esophoria and orthophoria. Exophoria, characterized by a lateral deviation of the eyes due to disrupted binocular fusion, is often associated with exotropia, a form of strabismus where the eyes deviate laterally (Maqbool, 2021).

Phoria frequently occurs in children with strabismus, and corrective surgery can unmask existing phorias. Identifying phoria is crucial for tailoring strabismus surgery to optimize binocularity within normal limits (Jung et al., 2016). Therefore, administering the TVPS in children suspected of having visual perception issues can help detect phoria and other vision problems promptly and accurately.

Numerous studies indicate that exophoria is more prevalent than esophoria, which may explain the associations found between exophoria and low TVPS scores in this research (Maqbool, 2021; Hashemi et al., 2020; Wajuihian, 2017). Additionally, exophoria is commonly linked to myopia, suggesting that both conditions could impair visual perception and the binocular vision needed for various visual tasks.

Sustaining binocular function requires dynamic processes, including peripheral fusion, tonic vergence, and vergence adaptation (Brodsky, 2020). These functions help minimize phoria, stabilizing binocularity. Phoria adaptation might enable some children with this issue to achieve better TVPS scores by recalibrating extraocular muscles for visual axis realignment and restoring the fusional range necessary for normal vergence function. However, the effectiveness of phoria adaptation depends on the fast fusional vergence system, meaning that the type and severity of fusional deficits can directly affect the ability to resolve binocular dysfunction and, consequently, influence TVPS performance.

These processes likely account for the variations in TVPS scores observed among children with phoria and/or fusional vergences in this study.

Previous studies have established associations between binocular vision and visual perception, often assessing perceptual function using the Test of Visual Perceptual Skills (TVPS), as done in this research (Argilés et al., 2023; Hård et al., 2004; Ho et al., 2015; Ibrahimi et al., 2021). For instance, Ibrahimi et al. (2021) found that children with strabismus and esotropia exhibited reduced TVPS scores for form constancy, with the lowest scores observed in those with impaired accommodative function. Similarly, children with exotropia and poor accommodation showed diminished form constancy scores. This suggests that preserving accommodative function may help mitigate the negative effects of strabismus on visual perception.

In this study, impaired accommodation was significantly associated with low form constancy scores, supporting Ibrahimi et al.'s findings. Additionally, it was found that impaired stereoacuity adversely affected TVPS scores for visual discrimination and visual closure—relationships not identified by Ibrahimi et al., who focused solely on children with diagnosed strabismus.

This research involved assessing near cover testing for strabismus, which was significantly predictive of low scores in form constancy and visual memory. As strabismus is a prevalent issue impacting binocularity, this finding helps address the core research problem, indicating that impaired binocular vision negatively affects specific visual perception abilities as measured by the TVPS.

Ibrahimi et al. (2021) also examined children with amblyopia and found lower scores for spatial relationships and visual closure compared to those without amblyopia. Since amblyopia negatively impacts binocular vision, these findings further support this research, showing that low scores in spatial relationships and visual closure were significantly related to exotropia, impaired near point of convergence, accommodation, and stereoacuity.

In a study measuring visual perception using the TVPS, Ho et al. (2015) found a significant association between near visual acuity and the visual discrimination and spatial relationship domains ($p<0.05$), although these factors accounted for only 1-3% of the variance in visual perception function. Contrarily, this research did not find that visual acuity problems affected visual perception abilities.

While it might be expected that near visual acuity would not greatly impact visual perception—since acuity primarily measures sharpness rather than the ability to distinguish differences between objects—significant impairments could lead to distorted perceptions. Severe acuity loss may cause individuals to struggle with visual memory and sequential memory tasks, preventing them from recognizing target images. This could also affect other TVPS domains, like figure-ground perception, where detail and sharpness are crucial.

These findings highlight the potential limitations of the TVPS, as visual acuity issues could lead to underestimating visual perception function, resulting in lower scores. However, this study ensured that children with acuity problems received appropriate refractive corrections and sufficient adaptation time, likely reflecting valid deficits in perceptual function across the cohort.

Two prior studies have employed the TVPS to assess visual perception function. Argilés et al. (2023) found no significant differences in visual discrimination, visual memory, spatial relationships, form constancy, figure-ground, or visual closure between school-aged children with and without strabismus and amblyopia. A difference in sequential memory was noted, but it was insignificant, slightly exceeding the 0.05 alpha threshold. These findings contrast with other studies, including this one, suggesting no relationship between binocular vision and visual perception. The authors did not provide a clear explanation for their results, acknowledging their divergence from previous research. Variations in methodology, sample size, and potential type II error may have influenced Argilés et al.'s findings.

In another study, Hård et al. (2004) reported that 87% of children with known brain lesions scored below the third percentile on the TVPS, with 85% exhibiting coexisting binocular vision issues, specifically strabismus. They found that good visual acuity did not mitigate low TVPS scores, indicating that intact or nearly normal acuity may not suffice to maintain visual perception in children with disturbed binocular vision. In contrast, this study revealed that 33-

57% of participants scored below the 25th percentile, representing a smaller proportion than in Hård et al.'s research. This discrepancy was expected, however, as the current study excluded children with brain lesions, which are known to adversely affect visual function (Sefi-Yurdakul, 2015; Sakki et al., 2022). Furthermore, Hård et al. utilized the first edition of the TVPS, while this study and others have used more recent editions, limiting direct comparisons.

Some studies have previously examined the relationship between binocular vision and visual perception in school children using non-TVPS assessments (Gligorović et al., 2011; Cavézian et al., 2010; Cavézian et al., 2013). This limits comparability with the current research, although some tests align with TVPS subdomains. For instance, Cavézian et al. (2013) found that children aged 4-7 with various ophthalmic issues, including strabismus and amblyopia (70.8%), exhibited significantly poorer visual perception than healthy controls, taking longer to complete tasks. Their visual perception assessment involved a shape-matching task that reflected the form constancy and visual discrimination domains of the TVPS. However, by focusing on a limited range of visual perception functions, Cavézian et al. may have underestimated the prevalence and nature of visual perception problems. The control group performed adequately, reducing concerns about comparative bias.

In this study, indicators of strabismus, such as impaired cover testing and eso- and exo-tropia, were significant predictors of low scores in form constancy and visual discrimination, supporting Cavézian et al.'s findings. However, this research also identified additional influences from accommodative function and stereoacuity on these scores, revealing more complexity in the visual functions affecting perception. Caution should be exercised in these comparisons, as Cavézian et al.'s study involved a small cohort of 24 children, making it underpowered and potentially prone to invalid results.

In earlier work by Cavézian et al. (2010), additional visual perception tests were administered to children with various neurovisual problems, primarily involving disorders of binocular vision. The results indicated that this neurovisual group performed worse than healthy controls on all three tests, with scores as follows: visual memory (3.61 vs. 3.54), embedded figures (21.9 vs. 22.1), and shape-matching (7.9 vs. 7.5). However, the differences were not statistically significant, likely due to a high risk of type II error from the small neurovisual group (n=10).

The visual memory test aligns with the TVPS, while the shape-matching task assesses form constancy and visual discrimination, and the embedded figures test corresponds with figure-ground perception. This study also found that poor visual discrimination and form constancy were evident in children with impaired binocular vision, supporting the adverse effects of binocularity on visual perception. Additionally, phoria at distance significantly predicted figure-ground ability, further reinforcing the interrelationship between binocularity and visual perception in school-age children.

Gligorović et al. (2011) assessed the relationship between strabismus, stereoacuity, and visual perception in visually impaired children aged 7-15 using the Acadia Developmental Abilities Test. The majority of the cohort had strabismus (65.5%) and impaired stereoscopic vision (69.1%). They found no significant differences in visual discrimination between strabismic and non-strabismic children ($p=0.114$), but strabismus was associated with significantly poorer visual memory ($p=0.037$). No significant variances in visual memory or discrimination scores were observed in children with and without impaired stereopsis ($p>0.05$).

In contrast, the current study found that impaired binocularity significantly affected scores in visual discrimination, visual memory, spatial relationships, and visual closure. This aligns with Ibrahimi et al. (2021), which noted significant reductions in visual memory and discrimination scores in children with esotropia (both $p<0.01$), but not in those with exotropia. The discrepancies with Gligorović et al. may stem from methodological differences. Additionally, impaired stereopsis in the current study impacted scores for visual closure, form constancy, and visual discrimination, further highlighting the complexities of visual perception in children with binocular vision issues.

The current study found that age significantly predicted visual memory and visual closure among school children aged 6-14 years. However, age was not a predictor for the other TVPS domains. This supports previous findings that older children generally perform better in visual perception tasks due to greater cognitive maturity and intellect.

While prior studies indicate that age influences visual perception—Gligorović et al. (2011) noted more favorable outcomes in older children compared to younger ones, and Ibrahimi et al. (2021) found similar trends—this study did not find consistent support for all domains assessed. Additionally, gender differences in visual perception were not examined in this research, though Ibrahimi et al. reported that boys performed better in figure ground and visual closure tasks, while girls excelled in visual and sequential memory.

These variances may stem from developmental differences in brain size, cortical density, and neural maturation (Ingalhalikar et al., 2014; Keith et al., 2011). Overall, the findings highlight the complexities of visual perception and suggest that age is a significant factor, while gender may also play a role in performance across different domains.

Functional imaging studies indicate gender differences in brain activation during cognitive tasks, suggesting that standardized visual perception tests adjusted for age may not provide reliable measures without considering gender and other influencing factors (Asano et al., 2014; Rubia et al., 2010). Asano et al. (2014) used functional magnetic resonance imaging to examine brain activation in children aged 6-18 during a visual perception task involving attention, working memory, and cognitive maintenance. They found a strong correlation between non-verbal cognitive abilities and visual perception, with notable activation in the right temporoparietal junction related to attention reorientation occurring only in males. However, no performance differences were observed, implying that other factors, especially age, may influence visual perception. Notably, no studies have investigated brain activation in response to validated visual perception assessments like the TVPS, highlighting a gap that warrants further research (Ganis et al., 2004; Calhoun et al., 2001).

4.2.2 Role and Evaluation of Machine Learning

Given the methodological differences in prior research, this study employed a novel approach to explore the relationship between visual perception, binocular vision, and other optometric functions in school children. Using machine learning and data mining via Orange software (Orange, 2024), this study presents original findings, marking the first use of this tool in optometric research. While machine learning offers powerful predictive analysis by handling large datasets and enabling real-world comparisons, the results should be interpreted with caution, considering the advantages and limitations of this approach (discussed in subsection 4.3).

Machine learning, increasingly used in health research, employs algorithms and statistical techniques to analyze data without the need for specialized programming. The Orange platform utilizes supervised learning, predicting outcomes based on trained data (Habehh and Gohel, 2021). Machine learning has shown strong predictive capabilities in medical fields. For example, Banoei et al. (2023) used it to predict recovery outcomes for traumatic brain injury patients, with high accuracy (Q2 >0.4-0.5, AUC 0.99). Similarly, Yang et al. (2023) demonstrated its effectiveness in analyzing polygenic scores for cancer outcomes. Predictive insights from machine learning can significantly impact decision-making and risk assessment in clinical practice (Swanson et al., 2023).

Recent reviews emphasize the potential of machine learning in ophthalmology, closely aligning with optometry due to the reliance on objective metrics and digital imaging (Srivastava et al., 2023; Ting et al., 2019). However, effective use of artificial intelligence (AI) requires large datasets for accurate analysis. The value of machine learning gained further attention during the COVID-19 pandemic, where telehealth combined with AI offered potential solutions for overcoming access barriers and easing clinician workload (Nikolaidou and Tsaousis, 2021). This is especially important given the increasing demand-capacity gaps in patient care (Charlesworth, 2022).

In optometry, machine learning can serve as a decision support tool by predicting vision problems based on specific scoring criteria for TVPS domains, or vice versa—forecasting visual perception ability from specific vision deficits (Srivastava et al., 2023). In this study, the use of Orange software generated nomograms that allow optometrists to input objective metrics (e.g., exophoria degree) and predict visual perception scores. This personalized approach could improve assessment and treatment decisions, tailoring interventions to individual needs. Moreover, identifying potential visual perception deficits may aid educational planning by accommodating these impairments. Overall, this research represents a significant advancement in optometry with promising implications for future practice.

Machine learning has been effectively used in ophthalmology, particularly in detecting diabetic retinopathy with high accuracy (AUC > 0.98) through deep learning models (Abràmoff et al., 2016; Gulshan et al., 2016). These results suggest similar potential for optometry, though larger datasets are essential for improving accuracy, as seen in previous studies. The application of machine learning in optometry could enhance decision-making, reduce false negatives, and improve efficiency in patient care. Standardization in future research is crucial to maximize its benefits in clinical practice.

Much of the deep learning research in ophthalmology has focused on predicting disease progression, such as visual field defects in glaucoma (Goldbaum et al., 2012; Wen et al., 2019). Similarly, this study aimed to predict the relationship between optometric metrics and TVPS scores using machine learning. The ability to predict the impact of binocular vision problems on visual perception in children could offer insights into their long-term effects on academic performance, quality of life, and psychological wellbeing. Visual function is critical to learning, particularly in younger children, where impairments can negatively affect academic outcomes (Wood et al., 2018; Harrington et al., 2022).

The expansion of machine learning in optometry could extend to predicting educational outcomes for school children based on impairments in binocular vision and visual perception. This information could guide treatment decisions, aligning interventions with academic goals and the preferences of children and their parents. For example, early or more aggressive treatment for strabismus may be considered to prevent its negative impact on learning and development. Additionally, machine learning could integrate developmental data to project how vision deficits affect social and developmental milestones, addressing the broader implications of vision disorders on children's lives and meeting the expectations of families.

4.3 Strengths and Limitations

The findings of this study should be considered in light of its merits and limitations. Key strengths include a comprehensive analysis of the relationships between visual perception, binocular vision, and other visual functions, contributing new knowledge to the field. A reasonable sample of school children aged 6-14 was used, enhancing the generalizability of the results. The novel application of machine learning to predict these relationships highlights the potential role of artificial intelligence in optometry and offers a foundation for future research. The use of the TVPS provided a standardized and robust assessment of visual perception abilities, addressing inter-study inconsistencies in the literature. Additionally, Bonferroni correction was applied to reduce the risk of type I error, ensuring the reliability of the findings.

Despite the strengths of this study, several limitations should be considered. The cross-sectional design allowed for a one-time analysis of the relationships between visual perception, binocular vision, and other visual functions, but it did not capture how these relationships change with age or development. This limits the ability to assess long-term evolution or causality between these factors. Additionally, the use of machine learning software prevented the study from accounting for confounding variables such as age, gender, cognitive development, and pre-existing medical conditions. As the PCA results indicated, other variables likely contributed to the unexplained variance (42%), highlighting the potential influence of unmeasured factors.

The study recruited a reasonable sample of school children (n=97) who completed the visual assessments, but the sample size was relatively small, limiting the generalizability of the findings. Additionally, the cohort's baseline characteristics may not represent children from different geographic regions due to varying prevalence of vision problems. However, the sample size was sufficient to reduce the risk of statistical bias and type II error, as confirmed by G-Power sample size calculations, though its adequacy for machine learning analyses remains uncertain. Given the small dataset, the machine learning outcomes may lack the accuracy and reliability needed for routine optometric use, though this work provides a feasibility sample for future research in this area.

Measurement bias may have arisen due to the incomplete validity of the TVPS in assessing visual perception. While the TVPS is considered a comprehensive and widely accepted tool for school-aged children, its internal consistency ranges (Cronbach alpha 0.68-0.81 for domains and 0.94 overall) may pose a risk of bias for some visual perception functions (Brown and Peres, 2018). Additionally, the TVPS has not been evaluated for responsiveness or floor/ceiling effects, which may limit its ability to detect changes over time or accurately capture the full range of visual perception abilities (Andrade, 2021a; Easson et al., 2018). Furthermore, the test's labor-intensive nature could lead to response-type biases, though the supervising investigator took steps to mitigate this by providing clear instructions and encouraging participants to ask for assistance with any issues during the assessment.

Alternative measures of visual perception, such as the Developmental Test of Visual Perception (DTVP) and the Motor-free Visual Perception Test (MVPT), were considered; however, their limitations outweigh those of the TVPS. While both tools have been validated for school-aged children, their validation samples were smaller, potentially impacting their external validity. Additionally, the DTVP and MVPT assess fewer visual perception functions than the TVPS, with the DTVP focusing on visuo-motor integration and the MVPT on visual memory and discrimination (Brown and Peres, 2018). This limited scope underscores the rationale for using the TVPS in this research to enhance the rigor and comprehensiveness of the findings. The TVPS stands out among visual perceptual assessments due to its non-motor design, allowing for a focused evaluation of perceptual abilities without the influence of motor skills. Other assessments, such as MVPT and DTVP, also address visual perception but differ in their approach and emphasis.

The MVPT, like the TVPS, avoids motor responses, making it a suitable option for individuals who may have motor impairments. It is often shorter in duration and commonly used for rapid screening purposes (Brown et al., 2003). In contrast, the DTVP integrates both motor and perceptual tasks, making it particularly effective for identifying combined motor and perceptual difficulties. This dual focus, while valuable for assessing visual-motor integration, means it places less emphasis on isolated perceptual skills compared to the TVPS (Hammill et al., 1993).

The TVPS is a highly reliable and comprehensive tool for evaluating visual perceptual skills. It offers significant advantages in isolating perceptual abilities compared to motor-integrated tests. However, practitioners should consider alternative assessments, like MVPT or DTVP, depending on specific clinical or educational needs.

4.4 Implications and Recommendations for Optometry

Based on the findings and their alignment with existing literature, several implications and recommendations for optometry practice have been developed. First, given the significant relationship identified between visual perception and binocular vision, it is crucial for optometrists to consider the various factors influencing the completion and outcomes of the TVPS. This is also relevant for other visual perception measures like the DTVP and MVPT, though these were not part of this study.

To address the variable relationships found, optometrists should conduct comprehensive vision screenings for children being assessed for visual perception. This approach will help identify any unrecognized vision issues that could bias TVPS results. Special attention should be given to problems related to convergence, accommodation, stereopsis, and other binocularity disorders, as these significantly affected TVPS scores in this research.

Additionally, it is vital to ensure that children tested for visual perception do not have cognitive or intellectual impairments that could hinder their performance on the TVPS. To enhance the assessment process, optometrists might consider incorporating supplementary measures like the Visual Attention Assessment, which has recently been piloted for younger children (Prieler et al., 2018). Furthermore, assessments that focus on broader attentional functions may also be useful in identifying attentional issues prior to conducting the TVPS (Mahone and Schneider, 2012).

Supervision during the TVPS is crucial for maintaining the focus and concentration of test takers, as distractions can lead to rushed responses and misinterpretations of visual perception abilities. Given the assessment's comprehensive nature, the authors might consider developing a shorter version to accommodate children who are easily distracted or have concentration difficulties. However, creating a streamlined assessment may be challenging due to the complexity of measuring various visual perception functions.

While the TVPS is widely regarded as a leading assessment tool, caution is warranted in its application. Cognitive or intellectual challenges may affect a child's performance, and the TVPS does not assess broader cognitive functions, potentially leading to misdiagnosis of visual perception issues. Therefore, a thorough evaluation of both cognitive and visual functions is essential for informed management decisions. Such assessments can significantly influence treatment strategies, ultimately impacting children's educational potential, life opportunities, and overall health and well-being.

The findings indicate that a child's age significantly impacts visual perception functions, such as visual memory and visual closure. However, the lack of influence from other demographic factors, particularly gender, suggests a need for re-evaluating the TVPS's validation. Previous literature has highlighted gender differences in visual perception, notably in areas like visual closure, figure ground, and sequential memory (Ibrahimi et al., 2021).

Additionally, optometrists and TVPS developers should consider other variables that may affect scores, such as familiarity with cognitive tasks or "brain games," which could enhance performance on certain visual perception tasks. While the TVPS includes practice runs, this may not adequately reflect an individual's broader experiences with similar tasks. Conversely, these practice runs might not sufficiently prepare some children, potentially leading to biased scores.

One particular concern is the spatial relationships task, which showed no significant association with binocular vision in this study. This finding raises questions about whether the task is appropriately adjusted for the test taker's age. Further research is needed to assess its feasibility and validity. Notably, the developmental testing of the TVPS indicated high internal consistency for the spatial relationships domain, with Cronbach's alpha values ranging from 0.77 to 0.90 for ages 5-14 (Martin, 2017). This suggests that the validity concerns regarding this domain might stem from methodological biases in this research.

4.5 Implications and Recommendations for Machine Learning

Developing comprehensive databases could enhance our understanding of machine learning's potential role in optometry. While creating an international database to gather extensive optometric data is ambitious, the growing digitalization of healthcare systems and patient records in high-income countries suggests that this vision is attainable (Stoumpos et al., 2023). In the UK, the National Health Service (NHS) has received funding to digitalize electronic health records; however, not all trusts have adopted these systems, highlighting the complexities and barriers involved in this process (Department of Health, 2024).

To support and expedite the digitalization of the NHS, stronger policy and organizational efforts are necessary, alongside improved integration across health services. Specifically, standardizing the digitalization of optometric services throughout the UK is essential for collecting the data required for machine learning applications. Other countries, particularly in Scandinavia, have demonstrated the benefits of extensive population health data capture through established national patient health records, leading to significant research advancements that might have otherwise gone unexplored (Hägglund and Scandurra, 2022;

Laugesen et al., 2021). This study represents a proactive step toward enhancing patient health data systems and could serve as a catalyst for ongoing efforts to create a more efficient and integrated future in healthcare.

Chapter 5. Conclusion and Future Research

5.1 Concluding Statements

This research aimed to investigate the relationship between visual perception and binocular vision in school children aged 6 to 14 years. The introductory and literature review chapters highlighted a significant gap in the evidence regarding how these variables interact, generating uncertainty about the effects of binocular vision on visual perception in this critical age group. Without normal perception and binocular vision, children may face reduced academic performance and limited life opportunities. Therefore, understanding this relationship is essential for improving screening, surveillance, and management strategies.

In addition to examining the relationship between visual perception and binocular vision, this study explored the feasibility of using machine learning software to predict these associations, marking the first effort within optometry to leverage machine learning for such purposes. This innovation could drive advancements in both research and clinical decision-making.

Key objectives included assessing the suitability of the Test of Visual Perceptual Skills (TVPS) for children and identifying other optometric factors affecting TVPS scores. The findings confirmed a significant relationship between impairments in binocular vision—such as accommodation issues, phoria, vergence function, and stereoacuity—and suboptimal TVPS scores (≤25th percentile) in various visual perception functions, including visual discrimination, memory, spatial relationships, form constancy, figure-ground perception, and visual closure.

5.2 Recommendations for Future Research

This research provided substantial evidence of a strong relationship between visual perception and binocular vision in school children. All TVPS domains, except for sequential memory, demonstrated some connection to binocular vision. Future studies should aim to standardize the literature by using the TVPS as the primary measure of visual perception, allowing for meaningful comparisons across studies and enhancing our understanding of this relationship.

To strengthen the evidence base, it would be beneficial for future research to incorporate multiple measures of visual perception, such as the DTVP and MVPT, alongside the TVPS. This convergence of data could provide insights into the associations between binocular vision and specific visual perception tasks while also clarifying the uncertain relationship between binocular vision and spatial abilities.

The PCA revealed several residual factors that modestly influenced TVPS scores and optometric variables, highlighting the need to identify these factors for accurate assessments. Possible mediating variables include gender, cognitive development, and prior exposure to cognitive games, warranting further research to explore their effects. Understanding these influences could inform future revisions of the TVPS and other visual perception assessments, ensuring greater accuracy and reliability. Additionally, the potential for neuroplasticity raises questions about whether visual perception in children with binocular issues can improve over time.

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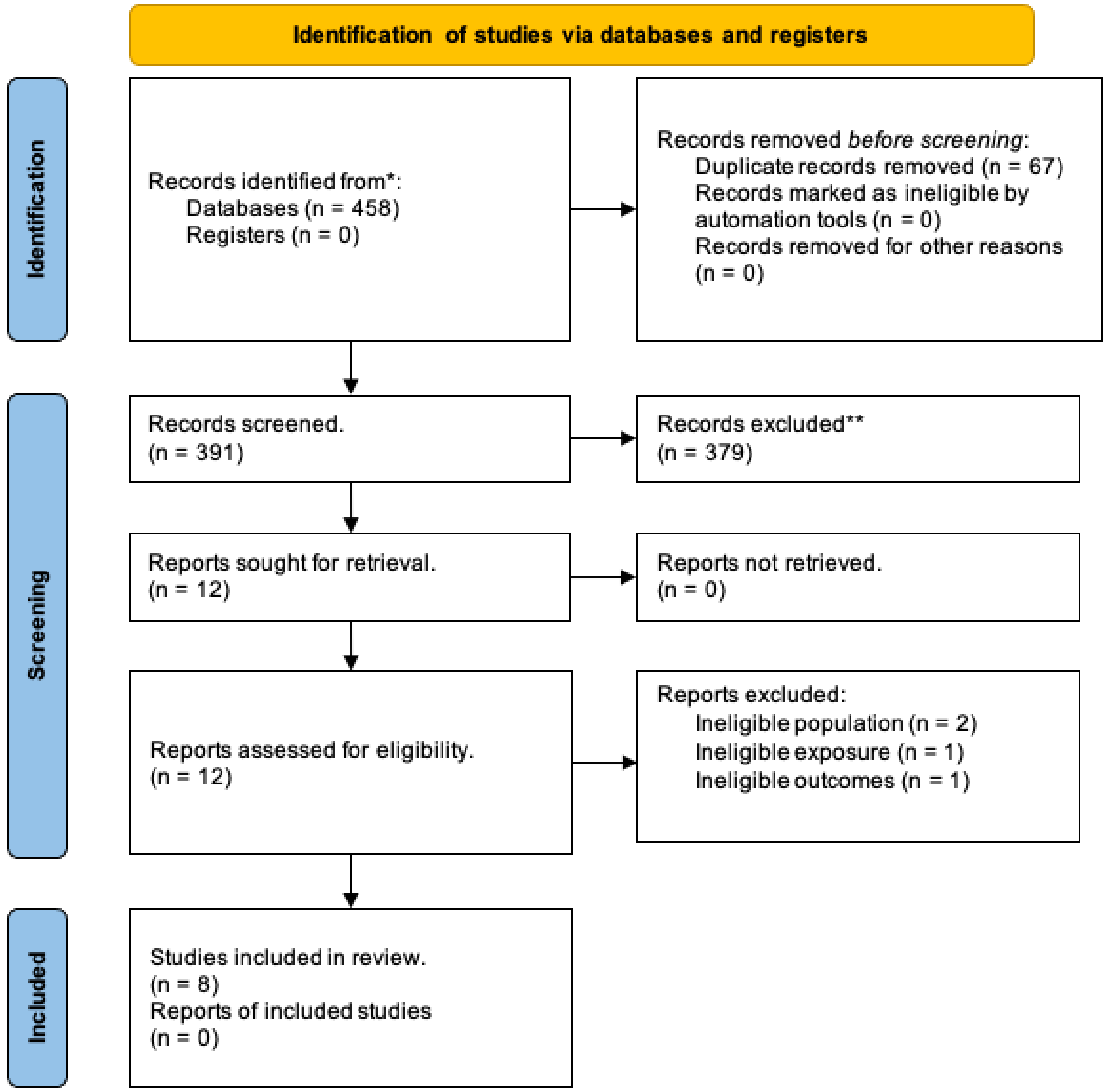
Appendices

Appendix 1. Filtering process for the background literature review using PRISMA diagram reporting.



Appendix 2. Overview of background evidence regarding the link between binocular vision and visual perception in school children.

Study	Measure of Visual Perception	Key Findings
Argilés *et al.* (2023)	TVPS	No significant differences in TVPS domain scores between children with binocular dysfunction and healthy controls were identified (all p>0.05)
Cavézian *et al.* (2010)	Shape matching task	Impaired visual perception function, as indicated by less favourable scores for all the three noted tests, was present among the test group (vision problems with most having strabismus), versus healthy controls
Cavézian *et al.* (2013)	Shape matching task	The scores for the visual perception test among those with vision problems (71% had strabismus) were significantly inferior to healthy controls, as was the completion time for the test (p<0.05)
Gligorović *et al.* (2011)	Acadia Developmental Abilities Test	Children with strabismus encountered significantly reduced scores for the visual memory and visual discrimination components, relative to expected or normal scores (both p<0.01)
Hård *et al.* (2004)	TVPS	Two thirds of children with brain lesions attained scores on the TVPS that were under the third percentile: the majority of subjects had strabismus and thus, a problem of binocular vision
Ho *et al.* (2015)	TVPS	Near visual acuity was significantly associated with the visual discrimination and spatial relationships (p<0.05) but these only contributed to 1-3% of the variance in visual perception function. 15% of the cohort had issues of stereopsis and strabismus but it was not clear whether these factors influenced visual perception abilities
Ibrahimi *et al.* (2021)	TVPS	There was a trend towards worsening TVPS scores in relation to strabismus (both esotropia and exotropia) and comorbid impairments of stereopsis
Sawamura *et al.* (2018)	Perception of three-dimensional shapes and feature discrimination tasks	Accuracy in the depth cue was significantly poorer among persons with strabismus with stereopsis, as compared to controls (70.5 v. 86.1, p=0.006)

Appendix 3. School Invitation Letter

Dear Sir/Madam,

I write to invite your school to participate in a research program that will form part of my doctoral studies in ophthalmic science, supervised by Professor Stephen J Anderson at Aston University in the UK. The aim of the research is the examine the association between a popular test of visual perceptual (TVPS) and binocular function in school age children. Any children recruited for the study will be provided, free of charge, a full eye examination at my practice in Kuala Lumper.

Children who are aged 6-14 years and meet the following criteria are eligible for the study:

- Have good level of vision (with or without glasses)
- No known ocular conditions, visually impairing conditions or oculomotor dysfunction (e.g. glaucoma, keratoconus, nystagmus)
- No known intellectual disabilities

This study has important implications for student learning, and I very much hope your school will be able to support the research program by encouraging student recruitment.

I attach herewith the Participant Information Sheet of the study for your consideration. Should you have any questions, please feel free to contact me through email or phone +6012-710 5855.

I look forward to your reply. Thank you.

Yours faithfully,

Tong-Keat Tien
Optometrist
Sun Time Vision Specialist
Kuala Lumpur
Malaysia

Cc: Prof. S.J. Anderson (BOptom, BSc, MCOptom, PhD)
Professor of Optometry & Visual Neuroscience
Aston University,
Birmingham B4 7ET
UK

Appendix 4. Ethics Approval

College of
Health and
Life Sciences

Aston University
Birmingham B4 7ET
United Kingdom

+44 (0)121 204 3000
aston.ac.uk

Stephen Anderson
06/02/2025

Study title:	Exploring the association between test of visual perceptual (TVPS) and binocular function in school age children: a research protocol
REC ID:	HLS21028

Confirmation of Ethical Opinion

Dear Stephen,

On behalf of the College of Health and Life Sciences Research Ethics Committee, I am pleased to confirm a favourable opinion for the above research on the basis described in the application form and supporting documentation listed below.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
Consent Form	1	25/04/2022
Ethics application form	1	25/04/2022
Patient information sheet	1	25/04/2022

Yours sincerely,

Dr Claire Stocker
Chair of the Life and Health Sciences Research Ethics Committee

Appendix 5. Adult Consent Form

Aston University
BIRMINGHAM UK

[Exploring the association between

test of visual perceptual (TVPS) and binocular function in school age children]

Consent Form

Name of Chief Investigator: <u>Mr Tong Keat TIEN, Prof Stephen J Anderson and Prof Timothy S Meese</u>

Please initial boxes

1.	I confirm that I have read and understand the Participant Information Sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2.	I understand that my child's participation is voluntary and that we are free to withdraw at any time, without giving any reason and without my legal rights being affected.	
3.	I agree to me and my child's personal data and data relating to us collected during the study being processed as described in the Participant Information Sheet.	
4.	I agree to take part in this study.	

Name of Participant

Name of Person Giving Consent	Date	Signature
Name of Person Receiving Consent	Date	Signature

REC: [1852], [Version 1], [YOU WILL NEED TO ADD A DATE WHEN YOU SUBMIT]

Appendix 6. Adult Participant Information Sheet

Aston University
BIRMINGHAM UK

Exploring the association between test of visual perceptual (TVPS) and binocular function in school age children

Participant Information Sheet

Invitation

We would like to invite you to take part in a research study.

Before you decide if you would like to participate, take time to read the following information carefully and, if you wish, discuss it with others such as your family, friends or colleagues.

Please ask a member of the research team, whose contact details can be found at the end of this information sheet, if there is anything that is not clear or if you would like more information before you make your decision.

What is the purpose of the study?

This study aims to investigate the relationship between visual perception abilities and binocular vision among school children aged 6-14 years.

Previous studies have explored the issues of visual perception and binocular vision dysfunction in children, but few have ascertained whether such problems are associated with one another. Hence, this study aims to further understand the relationship between visual perception and binocular vision.

Why have I been chosen?

You and your child are being invited to take part in this study because you have shown an interest in participating by contacting and leaving us your basic contacts (name, phone number and email address) after seeing our recruitment advert at your child's school or at the researcher's optical shop, and because your child meets the criteria for the study. This is:

- Age 6-14 years
- Have good level of vision (without glasses or with glasses)
- No known ocular conditions, visually impairing conditions or oculomotor dysfunction (e.g. glaucoma, keratoconus, nystagmus)
- No known intellectual disabilities

REC[**1852**], [Version 1], [PLEASE ADD DATE WHEN SUBMITTING]

What will happen to me if I take part?

After receiving your consent of participation and before the assessment day, a questionnaire which includes questions about demographic and any relevant clinical data, e.g. age, gender, ethnicity, medical and surgical history and optometric history, etc. will be provided you through email to complete and then submit to us. Afterwards, your child will be required to attend a two hour research visit at Sun Time Vision Specialist at Kuala Lumpur. The research visit will involve the following tests in sequence:

- Eyesight
- Eye teaming ability - skill that allows both eyes to work together in a precise and coordinated way
- Eye focusing ability - ability of the eye to change its focus from distant to near objects (and vice versa)
- Three-dimensional (3D) perception ability
- Visual perception skills - ability to organize and interpret the information that is seen and give it meaning

Do I have to take part?

No. It is up to you to decide whether or not you wish to take part.

If you do decide to participate, you will be asked to sign and date a consent form. You would still be free to withdraw from the study at any time without giving a reason.

Will my taking part in this study be kept confidential?

Yes. A code will be attached to all the data you and your child provide to maintain confidentiality.

Your personal data (name and contact details) will only be used if the researchers need to contact you to arrange study visits or collect data by phone. Analysis of your data will be undertaken using coded data.

The data we collect will be stored in a secure document store (paper records) or electronically on a secure encrypted mobile device, password protected computer server or secure cloud storage device.

To ensure the quality of the research, Aston University may review your data to check that it has been recorded accurately. If this is required, your personal data will be treated as confidential by the individuals accessing your data.

What are the possible benefits of taking part?

There are no direct benefits to you in taking part in this study, however the data gained will allow us to see whether there is a relationship between binocular function and visual perceptual skills. This will also help to develop further research investigating how to help children whose academic performance have been influenced by their binocular dysfunction and/or perceptual abilities.

What are the possible risks and burdens of taking part?

All procedures involved in this study are extremely low in risk.
They are the same or similar procedures to those carried out during a routine eye examination and all infection control procedures will be adhered to.
In the unlikely event that your child experiences any eye discomfort, fatigue, or other problems during the study, please let the researcher know, so they can stop the study and/or give you a break.

What will happen to the results of the study?

The results of the study may be published as part of a Tong Keat TIEN thesis, in scientific journals, and/or presented at conferences. If the results of the study are published, the identity of your child will remain confidential.

A lay summary of the results of the study will be available for participants when the study has been completed and the researchers will ask if you would like to receive a copy.

Expenses and payments

Non-reimbursable transportation expenses and time.

Who is organising this study and acting as data controller for the study?

Aston University is organising this study and acting as data controller for the study. You can find out more about how we use your information in Appendix A.

Who has reviewed the study?

This study was given a favorable ethical opinion by the Aston University Research Ethics Committee.

What if I have a concern about my participation in the study?

If you have any concerns about your participation in this study, please speak to the research team and they will do their best to answer your questions. Contact details can be found at the end of this information sheet.

If the research team are unable to address your concerns or you wish to make a complaint about how the study is being conducted you should contact the Aston University Research Integrity Office at research_governance@aston.ac.uk or telephone 0121 204 3000.

Research Team

Contact Name : Mr Tong Keat TIEN
Contact Number : +60 127105855
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Contact Number : +44 0121 204 4130
E-mail : t.s.meese@aston.ac.uk

Thank you for taking time to read this information sheet. If you have any questions regarding the study please don't hesitate to ask one of the research team.

Appendix A: Transparency statement

Aston University takes its obligations under data and privacy law seriously and complies with the Data Protection Act 2018 ("DPA") and the General Data Protection Regulation (EU) 2016/679 as retained in UK law by the Data Protection, Privacy and Electronic Communications (Amendments etc) (EU Exit) Regulations 2019 ("the UK GDPR").

Aston University is the sponsor for this study based in the United Kingdom. We will be using information from you in order to undertake this study. Aston University will process your personal data in order to register you as a participant and to manage your participation in the study. It will process your personal data on the grounds that it is necessary for the performance of a task carried out in the public interest (GDPR Article 6(1)(e). Aston University may process special categories of data about you which includes details about your health. Aston University will process this data on the grounds that it is necessary for statistical or research purposes (GDPR Article 9(2)(j)). Aston University will keep identifiable information about you for 6 years after the study has finished.

Your rights to access, change or move your information are limited, as we need to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, we will keep the information about you that we have already obtained. To safeguard your rights, we will use the minimum personally identifiable information possible.

You can find out more about how we use your information at https://www.aston.ac.uk/about/statutes-ordinances-regulations/publication-scheme/policies-regulations/data-protection or by contacting our Data Protection Officer at dp_officer@aston.ac.uk.

If you wish to raise a complaint on how we have handled your personal data, you can contact our Data Protection Officer who will investigate the matter. If you are not satisfied with our response or believe we are processing your personal data in a way that is not lawful you can complain to the Information Commissioner's Office (ICO).

Appendix 7. Age-appropriate Information Sheet

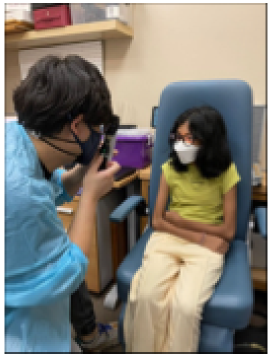
Aston University
BIRMINGHAM UK

CHILDREN INFORMATION SHEET

Exploring the association between tests of visual perceptual (TVPS) and binocular function in school age children

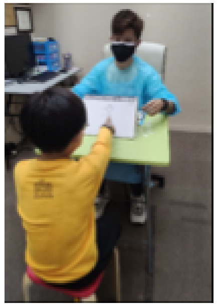
You will be coming to my optometric practice to have your eyes measured. This will be done in two ways:

1. The picture below shows the first way this will be done:



I will shine a light into your eyes while holding a lens in front of you. This is not painful in any way, and will only take about 30 minutes.

2. The picture below shows the second way this will be done. You will be asked about some drawings in a book, and you need to choose an answer from the options given.



Again, this method is not at all painful, and it will only take 30 to 40 minutes to complete.

Your parents or carer can stay with you the whole time. Both tests will only take about one hour, and then you are free to go home. If you have any questions, just ask me, Tong Keat Tien, or your Mum or Dad.

REC: [1852], [Version 1], [18 May 2022]

Appendix 8. Age-appropriate Consent Form

Aston University
BIRMINGHAM UK

CHILDREN ASSENT FORM

Project Title: Exploring the association between tests of visual perceptual (TVPS) and binocular function in school age children

Name of Chief Investigator: Mr Tong Keat TIEN

Prof Stephen J Anderson

Prof Timothy S Meese

1.	I understand what the project is all about.	
2.	I have asked all the questions I want and I understand the answers.	
3.	I can ask more questions at any time.	
4.	I do not have to take part if I do not want to, and can stop at any time.	
5.	I am happy to take part.	

Name of participant : ______________________________

Age : ______________________________

Signature : ______________________________

Date : ______________________________

Name of person receiving consent : ______________________________

Signature : ______________________________

Date : ______________________________

REC: [1852], [Version 1], [16 May 2022]