RESEARCH PAPER

An Objective Virtual Reality–Based Approach for Assessing Depth of Interocular Suppression in Amblyopia

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ABSTRACT

Background: Interocular suppression is an essential clinical measure in the pathologies of amblyopia and binocular vision; nevertheless, the current clinical methods of measurement of the depth of suppression are highly subjective and un-reliable in children and non-verbal individuals. The purpose of the current research was to design and test an objective, quantitative system of the virtual reality (VR) based on interocular suppression to evaluate the depth of the interocular suppression by relying on an optokinetic nystagmus (OKN) paradigm.

Methodology: To enroll the participants, an ethical approval and an informed consent were obtained, and sixty-nine patients with monocular amblyopia (mean age: 16.67 ± 0.7 years) were included. Ophthalmic assessment was done to the participants. The elicitation of OKN responses under the conditions of binocular viewing was done through a mobile based VR system that displayed horizontally moving red and black vertical strips. Eye movements were filmed by a camera outside the body so as to detect objectively OKN. Suppression depth was measured using contrast modulation in the VR environment and compared with the clinical depth measurement of the Worth four dot test using Neutral Density (ND) filters. The statistical analysis comprised of Shapiro Wilk test of normality, rank correlation of Spearman, Bland Altman analysis of agreement and intraclass correlation coefficient (ICC) of inter-rater reliability.

Results: A robust and statistically important correlation was observed between VR-based and ND filter measurements of suppression depth (Spearman's $\rho = 0.80$, $p < 0.001$). Bland–Altman study showed that 88.4% of paired measurements fell within the limits of agreement (–0.846 to +0.806), indicating acceptable agreement between methods. Inter-rater reliability for VR-based depth assessment was exceptional (ICC = 0.94; 95% CI: 0.90–0.97).

Conclusion: The VR-based OKN system provides a reliable, objective, and quantitative measure of interocular suppression depth. Its strong agreement with conventional clinical tests and high reproducibility support its potential use in clinical and research settings, particularly for pediatric and non-verbal populations.

Keywords: Amblyopia; Interocular suppression; Virtual reality; Optokinetic nystagmus; Binocular vision; Suppression depth

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INTRODUCTION

About 2% of people have amblyopia, which is linked to reduced visual functions because of aberrant binocular contact during the formation of the visual system [1]. Although there are additional abnormalities in amblyopia which are both binocular and monocular in origin, these reduced visual functions are frequently described as instances of monocular vision deficiencies. Reduced stereoacuity and increased interocular reduction of the narrow-sighted eye are examples of binocular impairments.[1,3–9].

Binocular integration—the brain's capability to combine visual data from both eyes into a single it is essential for efficient and accurate visual functioning in daily life. This process allows for depth perception, spatial orientation, and enhanced visual performance in tasks requiring precision and coordination [10,11].

In addition to depth perception, binocular integration contributes to binocular summation, where visual performance (e.g., contrast sensitivity and acuity) is enhanced with both eyes work together than with one eye alone. This summation improves the visual clarity, performance even in low-light conditions as well as aiding other tasks such as reading, fine motor tasks, or threading a needle. [12,13].

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Recent study has focused a lot of attention on the significance of treating suppression in order to comprehend amblyopia. The Worth 4 Dot test with Neutral density filter[14] is a popular clinical test for suppression; however it is not an objective way of measuring the degree of suppression[8]

These subjective evaluations are more difficult for young children because they need patients' focus and particular responses during the testing process[15]. By varying the test distance from the screen to change the angle of view of dot separating[16]. one may ascertain the magnitude of a suppression scotoma. A calibrated neutral density filter can be used to diminish the relative brightness of objects in order to clinically evaluate the depth of suppression.[17] No research has been done to establish the extent and degree of suppression. We cannot depend on replies in the paediatric group since they might not be able to give accurate answers. The current study is a objective method for determining the degree of suppression.

Studies that accurately assess the extent of suppression are lacking. We cannot depend on replies in the paediatric group since they could fail to be able to give accurate answers. The current test is an objective method for determining the degree of suppression. In order to assist in the cure of amblyopia, we are going to design a gadget that allows us to find out objectively using the red and black strips which will be similar looks like OKN strips with VR device.

MATERIALS AND METHODOLOGY

Subjects

Sixty-nine individuals with monocular amblyopia were included in this study; their average age was 16.667 years (±0.7). The Academic Ethics Committee of Sankara Eye Hospital, Sri Kanchi Kamakoti Medical Trust, granted ethical approval for the study. The study is filed with the Clinical Trials Registry of India (CTRI), having the identifier CTRI/2024/07/071446 and was approved under proposal number SHE/LDH/EC/2023/001.

All subjects willingly gave their informed permission before the commencement of the studies, showing their desire to participate in the research. Every participant underwent a thorough screening, which included gathering their ocular history, evaluating their visual acuity, doing a refraction exam, administering the cover test, and performing direct ophthalmoscopy to examine the condition of the retina & optic nerve. Before the trial, these tests gave a comprehensive understanding of each subject's ocular condition.

Stimulus

Software with Customizable Visual Stimuli (Red and Black Strips)

The optokinetic stimulation software was connected to a virtual reality (VR) platform on a mobile platform. In particular, the software, which consisted of horizontally moving vertical strips, colored in red and black, was controlled by a smartphone that was firmly installed in a VR headset. This arrangement formed a complete visual field and hence removed any external visual distraction and focused the participant's complete attention of the participant on the stimulus. The engagements of the VR setup played a significant role in the uniformity of presentation of stimuli across all subjects and increased reliability in the measurement of visual suppression.

VR System to use in Immersive Testing.

The high-contrast moving strips are a constant repetitive horizontal movement across the visual field as the subject gazes into the VR display. This movement is aimed at stimulating an optokinetic nystagmus (OKN), a visually reflexive movement, that is, in the same direction as the motion. OKN is an established measure of the functional integrity of the subcortical and cortical visual pathways and a physiological measure of motion perceptions and visual interaction[18] This closed VR environment provides that the induced nystagmus is a direct result of the visual stimulus and not the result of ambient visual stimuli, and thus the visual processing and interocular suppression mechanisms are more accurately assessed.

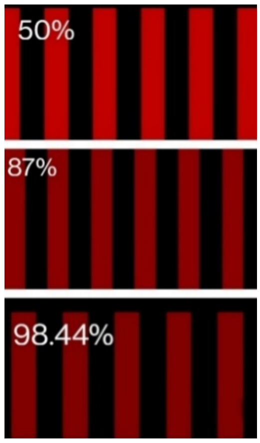


Figure 1: Illustrates the unequal depths of red and black strips.

An external endoscopic camera was positioned on the VR headset strategically in order to capture the ocular reactions in an objective manner as the optokinetic stimuli were being presented. The position of this camera was such as to give a clear lateral view of the eyes of the participant without interfering with the participant's visual field of the participant. It was real-time connected to a laptop through a wired interface to enable eye movements to be constantly live-streamed and recorded during the testing period. The camera was positioned such that it was not within the visual field of the subject so that it would not interfere with the immersive effect and fixation behaviour of the subject.

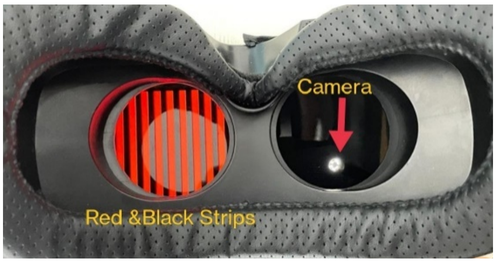


Figure 2: VR device with camera attached

Figure 3: shows the image from the camera while the test has been performed.

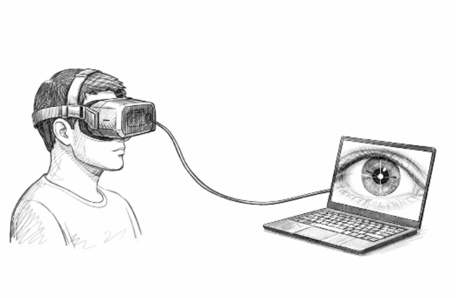


Figure 4: The system of VR, which is attached to the laptop. The examiner will be observing the laptop for nystagmus movement of the subject.

The main purpose of the camera system was to record and record optokinetic nystagmus (OKN) - a reflexive eye movement response to moving objects that is made up of alternating slow saccadic elements. When the red and black vertical strips were transferred horizontally over the VR display, the examiner observed the eye movements as the presence of rhythmic nystagmus, which is evidence of the active involvement of the visual motion-processing system. In the case of a track of the OKN, it proved that the participant was feeling and processing the visual stimulus. If the movement is present, the reduced contrast strips will be shown until there is no movement.

Correlation with Depth of Suppression Validation with Neutral Density Filter Test:

The depth of suppression was defined as the stimulus intensity ratio between dichoptically presented targets where the participant reported a change in response from suppression to fusion or simultaneous perception.

The current study examined the depth of suppression, which is the extent to which the visual input of one eye is suppressed in the case of binoculars. This was assessed using a dichoptic modulation technique within the VR-based optokinetic nystagmus (OKN) test and was compared with clinical results obtained through the Neutral Density Filter (NDF) test, a widely used subjective measure for evaluating suppression depth.

The VR strips were created to match the Neutral density filter. The neutral density filters are used with the log units matched with the red and black strips. The log units of the neutral density filters were 0.3log, 0.6log, 0.9log, 1.2log, 1.5log and 1.8log. In the same way, the contrast of the red and black strips was 50%, 75%, 87.5%, 93.75%, 96.8%, and 98%. So that the depth of the neutral density filter and VR strips should be similar. For example, if the NDF gives 0.3log which means 50 % of contrast will be reduced in the red and black strip.

By comparing these two assessments—the objective OKN-based contrast threshold and the subjective NDF A positive correlation between these two metrics would validate the VR-based approach as an effective, repeatable, and non-invasive alternative to subjective suppression depth assessment.

Table 1: Relationship between neutral density (ND) filter log units and the corresponding percentage reduction in contrast, illustrating graded attenuation of visual input for quantifying the depth of interocular suppression.

SL	Log units of ND filters	Percentage of Contrast reduction
1	0.3 log unit	50%
2	0.6 log unit	75%
3	0.9 log unit	87.5%
4	1.2 log unit	93.75%
5	1.5 log unit	96.8%
6	1.8 log unit	98.44%

Statistical analysis

Testing the data's normality with respect to the suppressed level in the Worth Four Dot test plus a virtual reality (VR) test, was the first stage in doing the statistical evaluation for this study. The Shapiro-Wilk Test was selected for the normalcy test because of its popularity in assessing the degree of normality of only one set of data. The study was not parametric since the Shapiro-Wilk test revealed that the sample did not have a normal distribution. Consequently, the link between the two evaluations could not be established using parametric tests like Pearson's r correlation. Instead, the association between suppression levels for Value Four Dots with the

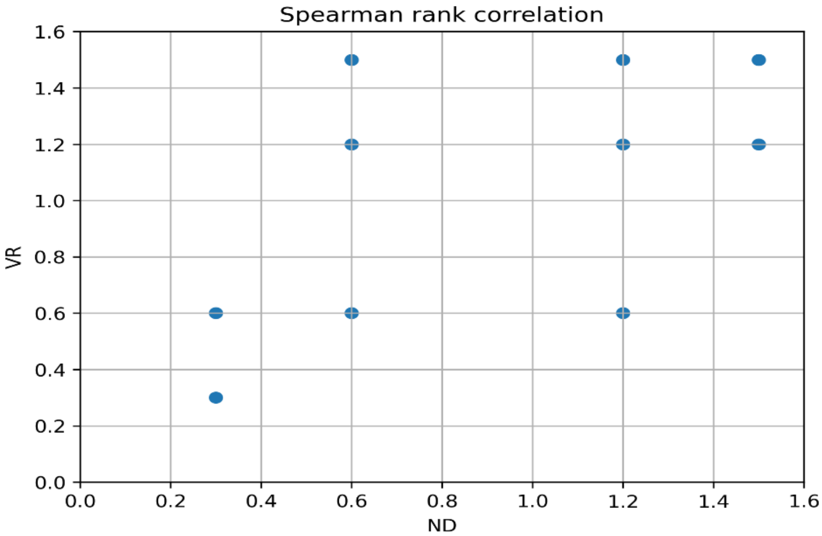
VR tests was determined using Spearman's rank coefficient.

RESULTS

The study's main goal was to find out if the Worth Four Dot test, which measures the degree of intraocular repression in people with monocular amblyopia, and the VR-based evaluation findings are related.

Testing for Validity

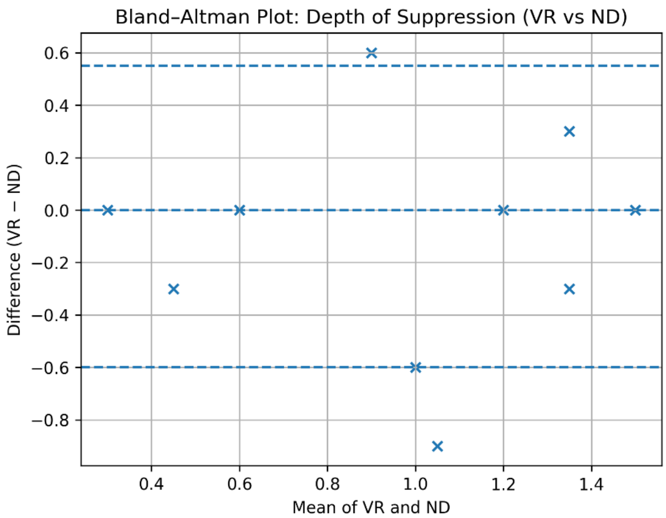
The correlation coefficient of Spearman's rank was utilised to evaluate concept and concurrent validity. This test assessed the correlation between the VR device's suppression measurements of the depth between both the techiques.



Graph 1: The scatter plot demonstrates a strong positive association between the VR-based measurement and the ND filter values. Spearman's rank correlation analysis showed a high correlation coefficient ($\rho = 0.80$), indicating that as the ND filter value increases, the corresponding VR measurement also increases in a similar ranked order. The relationship was statistically significant ($p < 0.001$), suggesting that the observed correlation is unlikely to have occurred by chance. This strong monotonic relationship confirms good agreement between the VR system and the ND filter method in assessing the depth of suppression.

Agreement Analysis

To visually assess the degree of consistency between the VR-based suppression data and clinical reference standards, Bland-Altman plots were constructed in addition to correlation. This investigation determined if the VR system overestimated or underestimated the suppression in comparison to the conventional methods. The overall distribution of the differences was used to determine if systematic bias existed or not, and the boundaries of agreement value (mean variance + 1.96 deviations from the mean) were calculated.



Graph 2: shows how closely the measurements of depth of suppression obtained using the VR system match those obtained using the ND filter test. The overlap between the two sets of measurements indicates that both methods produce

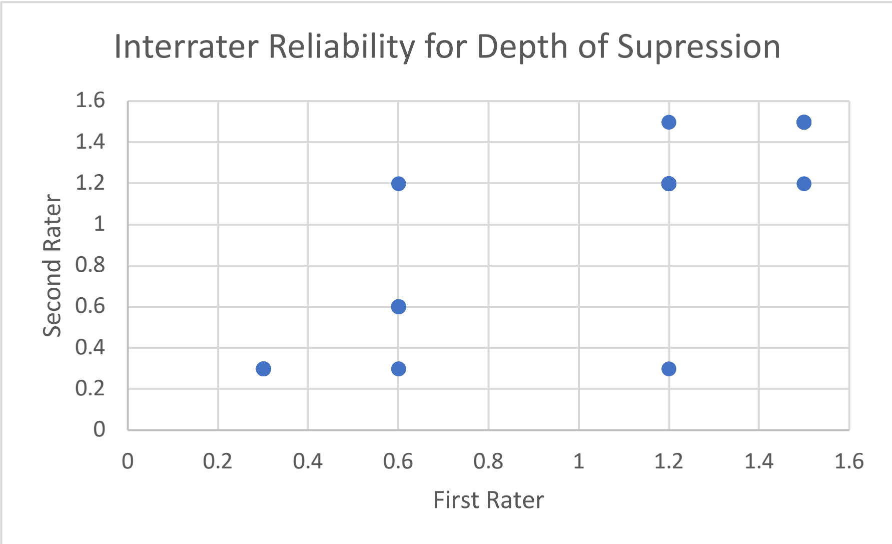
similar results for most participants. An agreement of 88% means that in the majority of cases, the VR-based measurements fall within an acceptable range of the ND filter values. This high level of agreement suggests that the VR system is reliable and comparable to the ND filter test for assessing the depth of interocular suppression, supporting its use as an alternative or objective assessment method.

Table 2: The Bland–Altman analysis shows that the difference between the two methods for measuring depth of suppression is very small. The mean bias of −0.020 indicates that both methods give almost the same average result. The limits of agreement range from −0.846 to 0.806, meaning that most differences between the two measurements fall within this range. Overall, this suggests good agreement between the methods and supports the reliability of the VR-based assessment compared with the ND test.

Bland–Altman Summary for Depth

Statistic	Value
Bias (mean difference)	−0.020
SD of differences	0.430
Lower LoA (bias − 1.96 SD)	−0.846
Upper LoA (bias + 1.96 SD)	0.806

Interrater Reliability
Two, blinded raters who were not aware of the results of another VR session independently interpreted the results of each VR session. This has enabled the evaluation of interrater reliability that is used to gauge the consistency of independent examiners. ICC (two-way random-efforts model to be consistent was calculated.



Graph 3: The Intraclass Correlation Coefficient (ICC) value of 0.94 indicates excellent inter-rater reliability, meaning that different raters provided very similar measurements. The 95% confidence interval (0.90 to 0.97) further supports this finding, showing that the agreement remains consistently high even when accounting for sampling variability. Overall, this result demonstrates that the assessment of depth of suppression is highly reproducible and not dependent on who performs the measurement.

DISCUSSION
This research was aimed at creating and testing a quantitative, objective, and in-depth interocular suppression evaluation method. The use of tests like the Worth Four Dot Test with Neutral density filter Test, though still standard in the diagnosis of amblyopia and strabismus, is dependent on patient compliance, attention, and verbal feedback [20,21,] which makes them unreliable when dealing with young children or non-verbal populations [22]. Moreover, although the semi-quantitative estimates of the size and depth of suppression are given by such manipulations as changing the distance of viewing or using graduated neutral density filters[23], they are all subjective and prone to examiner bias.

The lack of an objective instrument, a standardized measure of the degree of suppression, is a significant gap, particularly in terms of the significance of prompt and precise monitoring through early intervention in pediatric and neurodevelopmentally challenged groups[24]. New developments in dichoptic presentation, eye-tracking, and electrophysiological recordings (e.g., VEPs/SSVEPs) have shifted to be more objective [12], but a clinically viable delivery of both dimensions of suppression is currently not possible. Our device will complete this gap by using a virtual-reality-based optokinetic nystagmus paradigm, providing reflex-based depth thresholds not in any way reliant on conscious visual judgments or patients' reporting.

We discovered in this paper that a Spearman rank-order correlation of 0.80 ($p < 0.001$) indicates that the relationship between VR and W4DT measures is strong and statistically significant, and has a monotonic correlation. Practically, the larger the size of suppression of the VR test subjects, the larger the size of suppression in the W4DT, nearly without exception (88.4% of the depth of suppression measurements fall within the Bland-Altman limits of agreement of -0.846 to +0.806). This shows that the discrepancy between the VR and W4DT values of depth is within about 0.85 units in 88.4% of cases- this is satisfactory consistency, with these two techniques. An ICC of 0.94 means that there is a lot of agreement between two independent raters in the case of rating the depth of suppression. The high level of consistency is very accurate and reliable, as the 95% CI is tight (0.90-0.97).

Practically, this implies that all variability in the depth ratings would be due to real differences in subjects as opposed to lack of consistency in the judgment of raters- this substantiates the applicability of the method in multi-observer research and clinical testing. We can conclude that this device, based on VR used to regulate the complexity of suppression.

CONCLUSION

The results of this paper indicate that the VR-based optokinetic nystagmus system can be used to objectively measure and quantitatively assess the depth of interocular suppression. It is valid and consistent since the correlation with the Worth Four Dot Test is strong, with good agreement and high inter-rater reliability. The device overcomes some of the major limitations of standard suppression tests in the sense that, instead of relying on subjective patient feedback, it relies on reflex-based responses. The method is especially beneficial in cases of pediatric and non-verbal populations. Comprehensively, the VR-based system has a high potential as a viable clinical and research mechanism for determining the depth of suppression.

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