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Feasibility of virtual reality to induce and measure optokinetic after-nystagmus (OKAN): a pilot study

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Optokinetic nystagmus (OKN) is a reflexive eye movement triggered by repetitive motion in the visual field, characterized by a slow phase tracking the motion and a fast phase resetting the eye position. Following OKN, optokinetic after-nystagmus (OKAN) occurs in darkness, decaying over time and reflecting vestibular function. While OKAN provides valuable insights into vestibular disorders such as uni- or bilateral vestibulopathy and persistent postural perceptual dizziness (PPPD), traditional assessments require large and complex setups, limiting clinical application. This pilot study explores the feasibility of using a commercially available virtual reality (VR) headset with integrated eye-tracking to induce and measure OKAN. Twenty-two healthy participants (median age: 42 years, 54% female) with normal audiological and vestibular function were exposed to 60s of horizontal optokinetic stimulation. OKN was observed in 13 participants, with OKAN detected in 69% of these cases, consistent with traditional methods (55–90%). The median time constant (TC) of 18.75 ± 6.84s also aligns well with values reported for traditional methods (13.95–23.4s). This pilot study demonstrates that VR-based OKAN measurement is feasible and comparable to traditional methods, offering a promising tool for clinical applications in diagnosing vestibular disorders.

Optokinetic nystagmus (OKN) is a reflexive eye movement, triggered when observing continuous motion in the surroundings. This motion, referred to as the optokinetic stimulus (OKS) typically involves repetitive motion, such as alternating light and dark stripes or viewing the shifting landscape from a moving vehicle. OKN consists of two distinct phases: a slow phase, during which the eyes follow the motion, and a fast phase, quick resetting movement that brings the eyes back to their starting position. Together, these phases help stabilize the retinal image, allowing for smooth visual perception[1,2]. When the motion stops and the environment becomes dark, another phenomenon called optokinetic after-nystagmus (OKAN) occurs. OKAN is characterized by a gradual decrease in eye movements that were initiated during OKN, following an exponential pattern. This slowdown is quantified using the slow-phase eye velocity (SPV). SPV is a key metric in clinical tests of vestibular function, such as caloric testing[3,4]. The decay of SPV during OKAN is quantified by the time constant (TC), which represents the time it takes for SPV to reduce to 37% of its initial value[5,6].

The OKAN offers valuable insights into sensory integration processes and has been studied in relation to vestibular disorders, such as unilateral and bilateral vestibulopathies[7,8]. Studies indicate that in healthy individuals, the OKAN TC is typically symmetric, with equal durations in both directions. Vestibular dysfunctions, however, can cause directional asymmetries or generalized reductions in TC, resulting in a faster decline of OKAN TC on the affected side[9–12]. Despite its clinical potential, traditional methods for measuring OKAN are limited by the complexity of the required setup. The vast majority of studies examining OKAN have used mechanical optokinetic drums, such as those by Bertolini et al.[6,13], Gizzi et al.[14], and Jell et al.[8]. In these setups, eye movements in the dark are typically recorded using electro-oculography (ENG) or video-oculography (VNG). Some more recent studies have deviated from this traditional approach but still relied on external eye-tracking methods. For example, Kramer et al., explored stereoscopic visual display systems to elicit OKAN but used invasive intra-ocular scleral coils to measure eye movements[15]. Similarly, Guo et al., projected a virtual rotating drum onto a curved 115 cm screen and used EOG to examine the role of OKAN in visually induced motion sickness[16]. Additionally, Ohyama et al. investigated OKAN using an immersive environment but relied

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on VNG to measure OKN without assessing OKAN[17]. In this study, we aim to explore whether the build-in eye-tracking technology in Virtual Reality (VR) allows for non-invasive measurement of SPV. Simultaneously, VR can serve as an alternative to traditional setups by simulating optokinetic environments with high visual fidelity.

To our best knowledge, the use of build-in eye-tracking in VR to measure OKAN has not been previously studied. Our goal is to determine whether VR-based eye-tracking can effectively elicit and measure OKAN, and if so, assess whether VR-OKAN is ready for clinical implementation. By addressing the technical and methodological challenges of VR-OKAN, this research aims to lay the foundation for its broader clinical use.

Methods

Subjects

This pilot study was conducted as a cross-sectional investigation. The data from 22 healthy adult participants was obtained and analyzed at the University Hospital of Brussels between August and October 2023. Inclusion criteria were normal or corrected-to-normal vision, no history of light sensitive epilepsy, and no history of vestibular or neurological disorders. Exclusion criteria included recent use of vestibular-suppressant medication or susceptibility to visual dependence. The Visual Vertigo Analogue Scale (VVAS) was obtained for the latter, all participants with scores > 40 were excluded. For audiological assessment, air- and bone conducted hearing thresholds were measured using Pure Tone Audiometry (PTA). Air conduction thresholds of lower than 25 dB HL at 500, 1000, 2000 and 4000 Hz were accepted to be normal hearing. Given that vestibulopathy can influence OKAN, a video Head Impulse Test (vHIT) was performed on all participants using the Synapsys® vHIT Ulmer software. A normal vHIT result was defined as a vestibulo-ocular reflex (VOR) gain > 0.7, without any overt or covert saccades. Caloric testing was conducted when the vHIT was not possible with normal results defined as unilateral weakness of less than 25% and a sum of the maximum peak velocities of the slow-phase caloric-induced nystagmus being less than 6°/s[4,18].

Ethical approval and informed consent

Informed consent was obtained from all subjects. All experimental protocols were approved by the Ethical Committee of the University Hospital of Brussel (EC number: EC-2023-109) and the Medical Device Framework Board (ID number 68001). The study was in accordance with the ethical standards from the Declaration of Helsinki for research involving human subjects.

Equipment and setup

A commercially available VR headset (Pico Neo 3 Pro Eye®), equipped with integrated eye-tracking capabilities (sample rate: 90 Hz, LCD display, field of view: 98°), was used to deliver the OKS and to record eye movements both during the stimulation and afterwards in darkness (Tobii®). The interpupillary distance, the distance between the centers of the user's pupil, was self-adaptive (range 55–71 mm) to prevent image distortions. The VR headset was calibrated for each participant to ensure accurate gaze tracking and minimize measurement error. The experimental setup was conducted in a quiet, dimly lit room to minimize external distractions and ensure participant comfort. Participants were seated in an adjustable chair with head stabilization to reduce movement artifacts. The VR system was connected to a computer running custom software stimulus presentation and record eye movement data. The game engine *Unreal Engine 4* was used to create the visual stimulation, developed by One Bonsai (Belgium).

Test procedure

Participants were asked to wear the VR headset and were given up to 5 min to acclimate to the virtual environment. The acclimatization process was facilitated by exposing them to a neutral mountainous landscape. Participants were considered acclimated once they reported feeling comfortable within the VR setting, which happened in all the cases within 2 min. To calibrate eye movements participants were asked to track a moving dot across the screen while keeping their head stationary. The dot started in the center of the display, and then traversed to each corner of the screen, creating a cross-like movement pattern. Once calibration was completed, participants were immersed in a virtual environment displaying a high-contrast 3D optokinetic drum simulation. This drum comprised of alternating black and white vertical stripes with each bar extending 5.7°. The vertical bars moved horizontally at a constant velocity of 60°/s for a duration of 60 s. Stimulus parameters were standardized based on previous research for OKAN induction[9,10,19,20]. The subjects were instructed to focus on the center of the screen and avoid tracking the stripes during the OKS to maximize the reflexive 'stare' OKN[21]. Immediately afterwards, during the periods of darkness, the participants were asked to "look straight ahead" and the eye movements continued to be recorded for 30s, during which the OKAN was measured. The procedure was repeated for the opposite stimulus direction after a rest period of 2min to prevent fatigue or adaptation effects. The sequence of the movement directions was determined in advance using a randomized order. This bidirectional approach allowed for the assessment of potential asymmetries in OKAN responses. In total, four trials per participant were performed with two right-to-left and two left-to-right motion trials.

Data analysis

Eye movement data, including SPV and fast-phase saccades, were recorded at 90 Hz and processed using MATLAB[22]. Raw data were filtered to remove blinks, ensuring cleaner input for SPV calculation in both the OKN and OKAN phases. SPV, computed as the differences between consecutive eye position samples divided by the sample interval, was fitted with an exponential decay function, following Eq. (1):

$$SPV\left(t\right)=A^{*}\mathrm{e}^{-\mathrm{t}/\tau} \tag{1}$$

where A represents the onset amplitude, and τ is the time constant of the decay[23,24]. A moving median filter was applied to remove fast-phase saccades by replacing their velocities with the median of adjacent slow-phase samples. A 0.5-s window (45 samples) was used for this filtering, as shown in Figs. 1 and 2. The average amplitude A was defined over the last 15 seconds of OKN. The exponential decay function was fitted twice on the first 15 seconds of OKAN, yielding the final τ value: Initial fit using all available samples and refined fit after removing the 10% of samples with the largest deviations from the median-filtered SPV.

Statistical analysis

Statistical analyses were performed using RStudio R.4.3.1[25]. Data were first screened for normality using the Shapiro–Wilk test. Descriptive statistics (median, range and mean ± SD) were calculated for demographic data and OKAN parameters. A preplanned sub analysis was implemented where ambiguous or insufficient OKN responses were excluded from analysis. This exclusion was based on the rationale that an indistinct OKN response precludes the generation of a measurable OKAN. The percentage of excluded trials was documented. A Wilcoxon Signed-Rank Test was used to compare OKAN metrics between stimulus directions. A significant threshold of $p < 0.05$ was applied for all analyses. The test-retest reliability was calculated for each optokinetic stimulus (i.e., two right-to-left trials and two left-to-right trials) using Pearson's r.

Results

Subject characteristics

A total of 22 participants were enrolled in the pilot study, comprising 12 females (54%), with a median age of 42 years (interquartile range 22–87 years). Audiological findings were normal in all participants, with a mean PTA of 11.81 ± 7.83 dBHL. Vestibular testing via vHIT showed normal gains with no covert or overt saccades in the horizontal, anterior, or posterior semicircular canals. One participant could not complete the vHIT due to neck pain from cervical arthrosis. In this case, caloric responses showed normal vestibular function. Regarding the VVAS, all participants scored below the threshold of 40 out of 100, with an average score of 2.39 ± 4.69. The optokinetic stimulation was well tolerated by all participants, with no reports of significant motion sickness or discomfort.

Optokinetic nystagmus

Of the 22 participants, 9 were excluded (41%), including 5 participants whose OKN responses were not clear (23%) and 4 participants (18%), whose OKN terminated prematurely, with a mean duration of 45.85 ± 1.23 s. Among the remaining 13 participants, iterative averaging was used to calculate OKN parameters. The 10% largest deviations from the mean were excluded across five repetitions to ensure reliable and accurate parameter estimation. This approach helped maintain data integrity while reducing the impact of outliers.

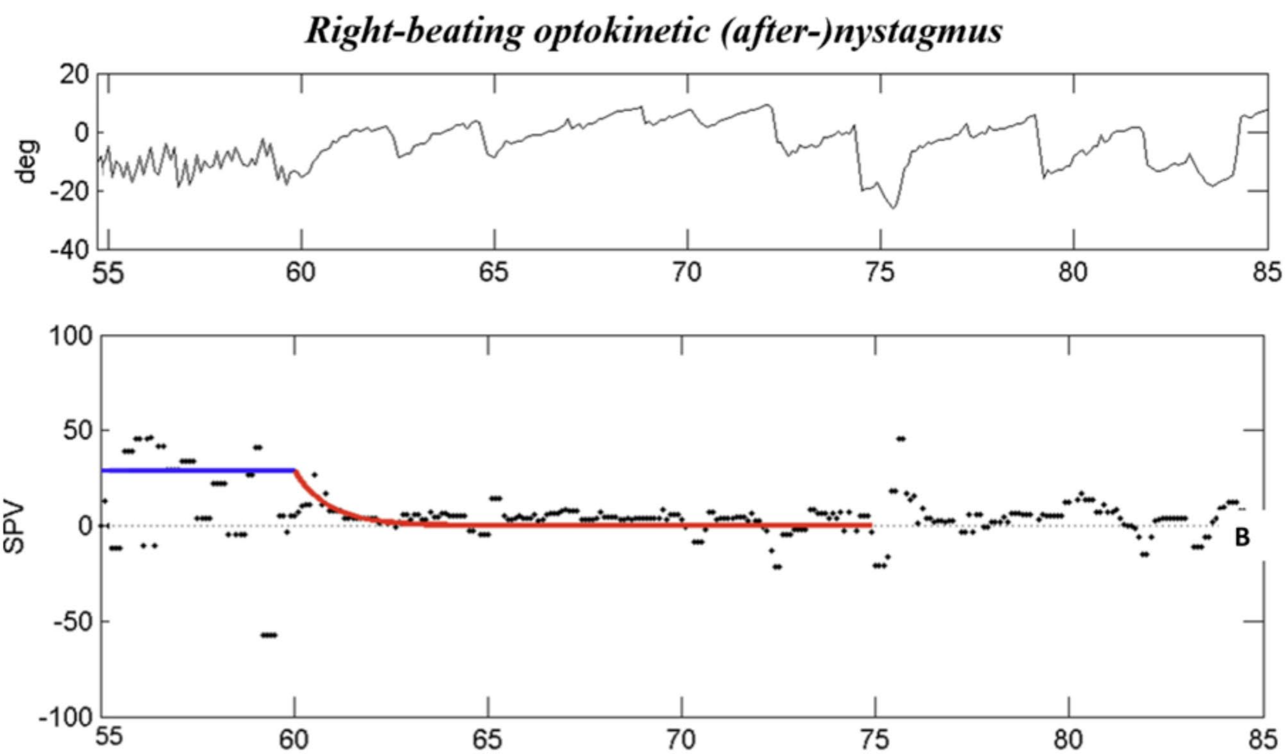

Fig. 1. This example demonstrates a right-beating optokinetic (after-)nystagmus. The graphs show both the eye position during optokinetic nystagmus (OKN) until second 60 and optokinetic after-nystagmus (OKAN) afterwards (**A**) as well as the corresponding slow-phase eye velocity (SPV) over time (**B**).

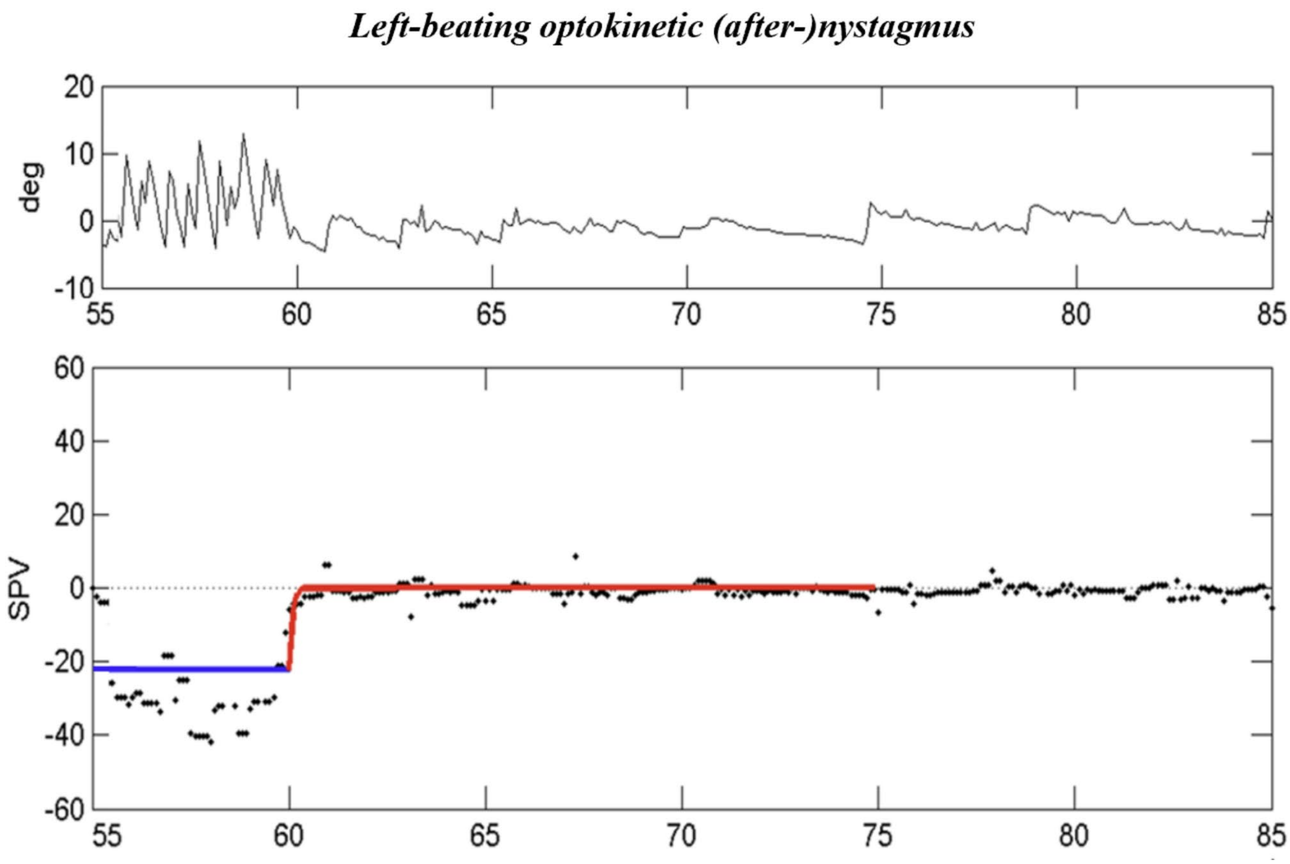

Fig. 2. This example demonstrates a left-beating optokinetic (after-)nystagmus. The graphs show both the eye position during optokinetic nystagmus (OKN) until second 60 and optokinetic after-nystagmus (OKAN) afterwards (**A**) as well as the corresponding slow-phase eye velocity (SPV) over time (**B**).

Optokinetic after-nystagmus (OKAN)
A measurable OKAN TC was observed in 9 participants (69% out of the analyzed sample, $n = 13$). In these cases, the VR-OKAN TC was successfully recorded in all four trials for 4 participants, in three trials for 2 participants, in two trials for 1 participant, and in a single trial for 2 participants. For 4 participants (31%), a clearly recognizable OKN was present but did not produce a measurable OKAN. The median OKAN TC across participants was 18.75 s (range 6.62–27.61 s), as shown in Fig. 3. No significant differences in OKAN TC values were observed between left-to-right and right-to-left stimulus directions ($z = -0.28$, $p = 0.77$), indicating directional symmetry in all participants. Additionally, there were no significant differences in VVAS scores between participants with and without measurable OKAN. The Pearson correlation coefficient showed a test-retest reliability of 0.67, indicating a moderate-to-strong positive correlation between the two trials. However, the small sample size may limit the accuracy and generalizability of these results.

OKN and OKAN data selection
Optokinetic nystagmus (OKN) is a reflexive eye movement triggered by repetitive motion in the visual field, characterized by a slow phase tracking the motion and a fast phase resetting the eye movement. To enhance the reliability of OKN and OKAN measurements, the final 15 s of OKN ($45 \leq t \leq 60$ s) and the first 15 s of OKAN ($60 < t \leq 75$ s) were analyzed. These intervals minimized noise while capturing the most robust response data. This analysis approach ensured consistent and meaningful comparisons across participants. Examples of averaged SPV responses during the OKN and OKAN phases are shown in Figs. 1 and 2. The OKAN SPV showed characteristic exponential decays following the cessation of the stimulus. The time constant (TC) for this decay was consistently observed across participants, with the onset amplitude of the decay aligning closely with the offset amplitude of the preceding OKN. Although a delay term, $(t - t0)$, was included in the fitting process, it did not substantially affect the resulting TC values.

Discussion
The results of this study demonstrate that an off-the-shelf VR headset with build-in eye-tracking can successfully induce and record OKAN in healthy individuals in a non-invasive manner. The median TC for VR-OKAN is 18.75 s, with a moderate test-retest reliability of 0.67, aligning well with traditional methods (13.95–23.4 s)[6,27]. Unlike conventional methods that require complex setups, such as rotating full-field drums or motor-driven turntables, VR offers a simpler and more accessible alternative.

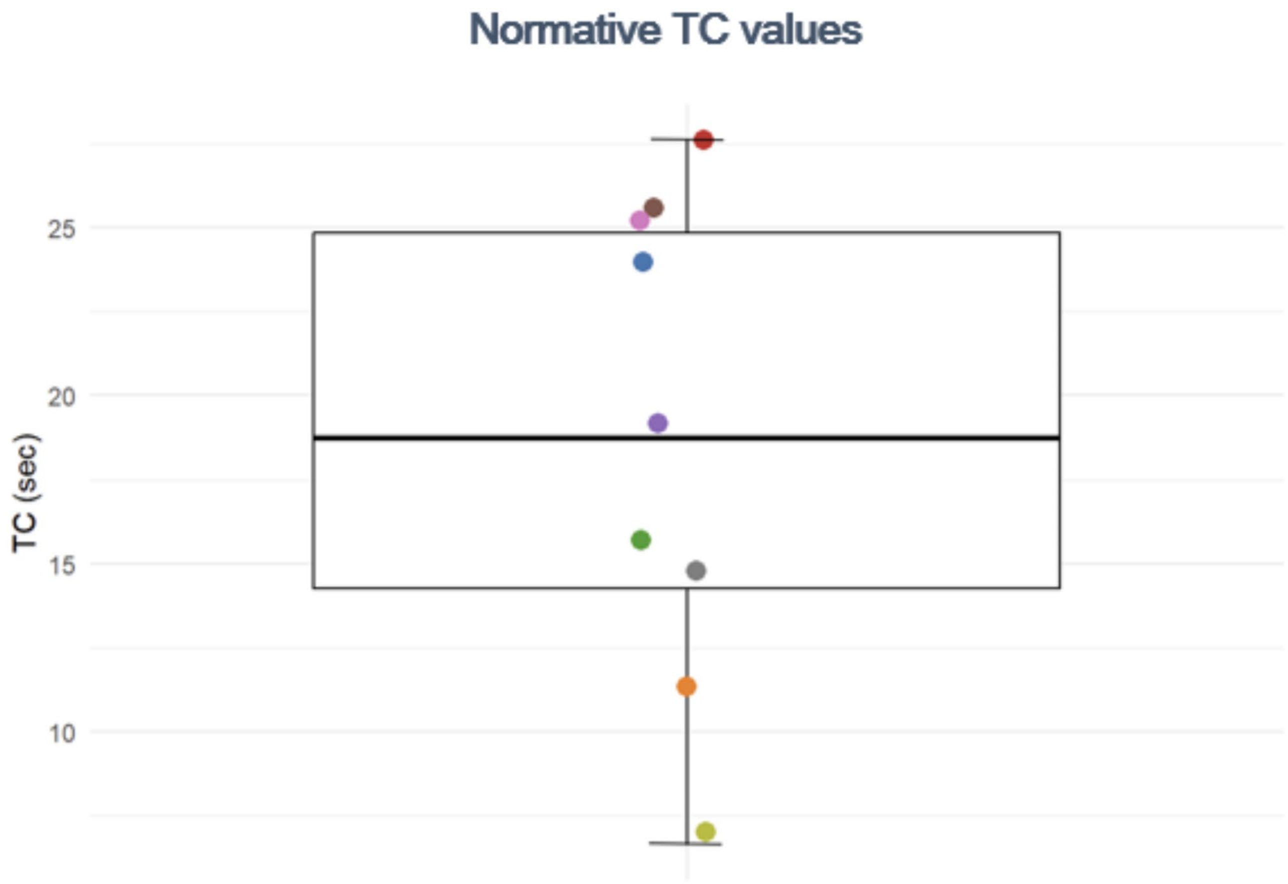

Fig. 3. Boxplot of the optokinetic after-nystagmus time constant (OKAN TC, seconds). The horizontal line in the middle of the box represents the median value (18.75 (6.62–27.61) s). The lower and upper boundaries indicate the 25th and 75th percentiles, respectively. Individual data points from all 9 participants are displayed in different colors.

However, VR-OKAN is not yet ready for clinical application. Specifically, a higher-than-expected proportion of poor-quality OKN responses (23%) was observed, with four participants showing signs of visual fatigue (18%). Kaminiarz et al. examined the OKAN with external eye-tracking and reported an exclusion of 21% of the OKN trials[28]. The increased % of excluded OKN in our study may be because the traditional parameters used do not translate seamlessly to the VR-based setups. Previous research has shown that an optimal OKS duration is approximately 60 s[12,29]. Additionally, studies investigating OKAN typically applied velocity stimulations of 60–90°/s[9,10,19,20,24], which is higher than the 30–40°/s typically used for inducing OKN[21]. While the rationale for these higher velocities has not always been explicitly stated, they are likely intended to sufficiently "charge" the velocity storage mechanism (VSM). The VSM, a neural network that integrates inputs from the vestibular, visual, and proprioceptive systems, is crucial for generating OKAN. During OKN, the VSM temporarily stores information about the slow-phase eye movements. When the motion stops, this stored activity is gradually released, producing the characteristic OKAN response. Higher stimulus velocities may enhance this storage process, ensuring stable and measurable OKAN responses that do not decay prematurely[7]. This suggests that VR stimulation may elicit different perceptual responses compared to traditional methods, highlighting the need to optimize parameters specifically for VR. Adjustments in stimulation duration, velocity, and visual stimulus design could improve the reliability of VR-based OKAN testing.

In this study, OKAN was detected in 69% of participants who exhibited OKN. This is consistent with previous studies that used traditional methods, indicating a prevalence range of 55–90%[27,30]. This variability in OKAN detection may result from environmental factors, as complete darkness is crucial for accurate measurements. One critical issue is the contrast between the black margins of the VR headset and the background illumination, which can provide unintended spatial orientation cues and interfere with the expected suppression of visual fixation. Both conventional methods and the LCD displays used in this study may have introduced residual light, potentially suppressing OKAN via central neural mechanisms[31]. Future research should explore the use of VR headsets with OLED or mini-LED displays, which achieve darker black levels compared to standard LCDs. Additionally, filters that lower the light intensity of the entire display could further minimize visual fixation. Investigation of the impact of VR display technology on OKAN measurements is warranted, as optimized display characteristics could lead to more accurate and reliable results.

Prolonged OKAN has been observed in individuals with visually induced motion sickness (VIMS) and visual dependence, a key feature of the chronic vestibular disorder persistent postural perceptual dizziness (PPPD). Guo et al.[16,30] showed significant correlations between OKAN TCs and nausea severity in VIMS. Similarly, Bos et al.,[23,32] reported slower nystagmus decay in individuals prone to motion sickness, suggesting a role for the VSM. Bertolini et al.[6] observed prolonged OKAN TCs in concussed patients reporting dizziness in visually complex environments. Both VIMS and visual dependence involve heightened sensitivity to visual motion and over-reliance on visual inputs for balance. We hypothesize that similar sensory integration dysfunctions underlie both conditions. Given the association between OKAN and visual hypersensitivity, participants in our study completed the VVAS to exclude those with PPPD. However, only 55% of participants reported no dizziness in visually challenging environments, aligning with existing literature showing that even healthy individuals may exhibit some degree of visual dependence[33]. Although no correlation was identified between VVAS scores and OKAN TC in our cohort, the potential remains that OKAN may reflect alterations associated with pathological visual dependence in PPPD. Given the association between OKAN and sensory integration dysfunctions observed in conditions such as PPPD, VR-based OKAN testing could provide a practical and non-invasive diagnostic tool for these disorders. Further research should focus on identifying normative thresholds and exploring its diagnostic accuracy in clinical populations.

Limitations

This study represents a pilot investigation into the feasibility of using VR-based eye-tracking technology for OKAN measurement. While the findings are promising, several limitations were identified that warrant further exploration. One key limitation was the inability to simultaneously analyze data while examining participants. This may have contributed to issues such as unrecognizable or prematurely ended OKNs. Incorporating real-time data analysis into VR setups could allow dynamic adjustments to testing protocols, such as providing individualized feedback to participants or modifying stimuli in real time to ensure robust OKN and OKAN responses. Furthermore, this study did not utilize traditional OKAN equipment for direct comparison. Instead, the results were referenced against previously published literature. While this approach provides useful context, a direct comparison with conventional methods would strengthen the validity of VR-based OKAN measurement.

Conclusion

This study demonstrated that VR goggles with integrated eye-tracking can evoke and measure OKAN in healthy participants. To our best knowledge, no other peer-reviewed studies have examined the use of VR-based eye-tracking as a viable tool for OKAN measurement. VR offers significant advantages over traditional methods, such as reduced space requirements, potential cost-effectiveness, and enhanced user-friendliness. Moreover, it can achieve the same normative values as conventional methods. However, VR-OKAN is not yet ready for clinical application. Continued research and larger-scale studies are needed to optimize the methodology and fully realize the potential of VR-based OKAN testing.

Data availability

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at the University Hospital of Brussels.

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References

1. Büttner, U. & Kremmyda, O. Smooth pursuit eye movements and optokinetic nystagmus. *Dev. Ophthalmol.* **40**, 76–89 (2007).
2. Hertle, R. W. & Hanna, N. N. Chapter 90—Supranuclear eye movement disorders, acquired and neurologic nystagmus. In *Taylor and Hoyt's Pediatric Ophthalmology and Strabismus*, 5th edn. (eds Lambert, S. R. & Lyons, C. J.) 933-52.e1 (Elsevier, 2017).
3. Agrawal, Y. et al. Presbyvestibulopathy: diagnostic criteria consensus document of the classification committee of the Bárány society. *J. Vestib. Res.* **29** (4), 161–170 (2019).
4. Strupp, M. et al. Bilateral vestibulopathy: diagnostic criteria consensus document of the classification committee of the Bárány society. *J. Vestib. Res.* **27** (4), 177–189 (2017).
5. Dellepiane, M., Medicina, M. C., Barettini, L. & Mura, A. C. Correlation between vestibulo-ocular reflex and optokinetic afternystagmus in normal subjects and in patients with vestibular system disorders. *Acta Otorhinolaryngol. Ital.* **26** (1), 20–24 (2006).
6. Bertolini, G. et al. Measuring optokinetic after-nystagmus: potential for detecting patients with signs of visual dependence following concussion. *J. Neurol.* **268** (5), 1747–1761 (2021).
7. Cohen, B., Uemura, T. & Takemori, S. Effects of labyrinthectomy on optokinetic nystagmus (OKN) and optokinetic after-nystagmus (OKAN). *Int. J. Equilib. Res.* **3** (1), 88–93 (1973).
8. Jell, R. M., Phillips, H. D., Lafortune, S. H. & Ireland, D. J. Comparison of caloric and OKAN tests in patients with vestibular deficits. *Adv. Otorhinolaryngol.* **41**, 201–205 (1988).
9. Hain, T. C. & Zee, D. S. Abolition of optokinetic afternystagmus by aminoglycoside ototoxicity. *Ann. Otol Rhinol. Laryngol.* **100** (7), 580–583 (1991).
10. Brantberg, K. & Magnusson, M. Asymmetric optokinetic afterresponse in patients with small acoustic neurinomas. *J. Vestib. Res.* **1** (3), 299–307 (1990).
11. Brantberg, K. & Magnusson, M. Galvanically induced asymmetric optokinetic after-nystagmus. *Acta Otolaryngol.* **110** (3–4), 189–195 (1990).
12. Reynders, M., Van der Sypt, L., Bos, J., Cools, W. & Topsakal, V. Systematic review and meta-analysis of the diagnostic value of optokinetic after-nystagmus in vestibular disorders. *Front. Neurol.* **15**. (2024).
13. Gygli, J. et al. Effect of the stimulus duration on the adaptation of the optokinetic afternystagmus. *Front. Neurol.* ;**12**. (2021).

14. Gizzi, M., Raphan, T., Rudolph, S. & Cohen, B. Orientation of human optokinetic nystagmus to gravity: a model-based approach. *Exp. Brain Res.* **99** (2), 347–360 (1994).
15. Kramer, P. D., Roberts, D. C., Shelhamer, M. & Zee, D. S. A versatile stereoscopic visual display system for vestibular and oculomotor research. *J. Vestib. Res.* **8** (5), 363–379 (1998).
16. Guo, C., Ji, J. & So, R. (eds) Could OKAN be an objective indicator of the susceptibility to visually induced motion sickness? In *2011 IEEE Virtual Reality Conference* (2011).
17. Ohyama, S., Nishiike, S., Watanabe, H., Matsuoka, K. & Takeda, N. Effects of optokinetic stimulation induced by virtual reality on locomotion: a preliminary study. *Acta Otolaryngol.* **128** (11), 1211–1214 (2008).
18. Strupp, M. et al. Acute unilateral vestibulopathy/vestibular neuritis: diagnostic criteria. *J. Vestib. Res.* **32** (5), 389–406 (2022).
19. Hain, T. C. & Zee, D. S. Velocity storage in labyrinthine disorders. *Ann. N. Y. Acad. Sci.* **656**, 297–304 (1992).
20. Brantberg, K. & Magnusson, M. Optokinetic after-nystagmus as an indicator of a vestibular side difference. *Acta Otolaryngol. Suppl.* **481**, 468–469 (1991).
21. Knapp, C. M., Gottlob, I., McLean, R. J. & Proudlock, F. A. Horizontal and vertical look and stare optokinetic nystagmus symmetry in healthy adult volunteers. *Investig. Ophthalmol. Vis. Sci.* **49** (2), 581–588 (2008).
22. The MathWorks Inc. Version 9.13.0 ed. *Massachusetts* (2022).
23. Bos, J. E., Bles, W. & de Graaf, B. Eye movements to Yaw, pitch, and roll about vertical and horizontal axes: adaptation and motion sickness. *Aviat. Space Environ. Med.* **73** (5), 436–444 (2002).
24. Cohen, B., Matsuo, V. & Raphan, T. Quantitative analysis of the velocity characteristics of optokinetic nystagmus and optokinetic after-nystagmus. *J. Physiol.* **270** (2), 321–344 (1977).
25. R Core Team. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing V, Austria. https://www.R-project.org/ (2024).
26. Fletcher, W. A., Hain, T. C. & Zee, D. S. Optokinetic nystagmus and afternystagmus in human beings: relationship to nonlinear processing of information about retinal slip. *Exp. Brain Res.* **81** (1), 46–52 (1990).
27. Zasorin, N. L., Baloh, R. W., Yee, R. D. & Honrubia, V. Influence of vestibulo-ocular reflex gain on human optokinetic responses. *Exp. Brain Res.* **51** (2), 271–274 (1983).
28. Kaminiarz, A., Krekelberg, B. & Bremmer, F. Expansion of visual space during optokinetic afternystagmus (OKAN). *J. Neurophysiol.* **99** (5), 2470–2478 (2008).
29. Brandt, T., Dichgans, J. & Büchle, W. Motion habituation: inverted self-motion perception and optokinetic after-nystagmus. *Exp. Brain Res.* **21** (4), 337–352 (1974).
30. Guo, C., Chen, D., Wei, Y., So, R. & Cheung, R. Correlations between individual susceptibility to visually induced motion sickness and decaying time constant of after-nystagmus. *Appl. Ergon.* **63**, 1–8 (2017).
31. Lee, S. H., Kim, M., Kim, H. & Park, C. Y. Visual fatigue induced by watching virtual reality device and the effect of anisometropia. *Ergonomics* **64** (12), 1522–1531 (2021).
32. Bos, J. E. & Bles, W. Motion sickness induced by optokinetic drums. *Aviat. Space Environ. Med.* **75** (2), 172–174 (2004).
33. Powell, G., Derry-Sumner, H., Rajenderkumar, D., Rushton, S. K. & Sumner, P. Persistent postural perceptual Dizziness is on a spectrum in the general population. *Neurology* **94** (18), e1929–e38 (2020).

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Author contributions
M.R., J.B., A.M. and I.F. were responsible for the design and outline of the work. J.B. and M.R. were responsible for the interpretation of the data. M.R. wrote the main text of the manuscript for which I.F. substantially revised the content of the work. J.B. and M.R. prepared the figures. J.A. and M.R. were responsible for the statistical analysis. All authors reviewed the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
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