Review

Journal of Innovative Healthcare Practices (JOINIHP) 7(2), 173-186, 2026

Received: 29-Oct.-2025 Accepted: 17-Aug-2026

https://doi.org/10.58770/joinihp.1812996

Scientific and Technological Transformation in Vestibular Rehabilitation: Neurophysiology-Based, Personalized, and Integrated Approaches

Muhammed Celal ERYILMAZ[1*]

[1] Serbest Araştırmacı, Türkiye.

ABSTRACT

Vestibular rehabilitation therapy (VRT) is undergoing a paradigm shift toward a mechanistically informed, multisensory, and technologically integrated model. This narrative review synthesises current evidence on how this transformation is driven by advances in neurophysiology, diagnostic precision, and immersive technologies such as virtual reality (VR), which collectively enhance personalization and therapeutic efficacy. Traditional approaches that primarily targeted peripheral deficits are now complemented by strategies addressing central processing dysfunctions, cognitive-emotional comorbidities, and maladaptive sensory integration, particularly in conditions like Persistent Postural-Perceptual Dizziness (PPPD) and vestibular migraine. VR-based rehabilitation enables controlled manipulation of sensory inputs and task complexity, facilitating adaptation, habituation, and substitution—key neurophysiological mechanisms underlying vestibular compensation. Objective diagnostic tools, including the Video Head Impulse Test (vHIT) and Computerized Dynamic Posturography (CDP), provide individualized assessments of vestibulo-ocular reflex (VOR) function and sensory reweighting, guiding targeted interventions. Wearable sensors and mobile platforms further extend high-fidelity VRT into home settings, enhancing accessibility and adherence through real-time monitoring and feedback. Randomized controlled trials and meta-analyses support the clinical efficacy of VR-based interventions across peripheral and central vestibular disorders, with several studies reporting outcomes comparable, and in selected populations potentially superior, to conventional methods. Importantly, the management of complex cases increasingly relies on interdisciplinary collaboration among physical therapists, audiologists, neurologists, and mental health professionals. This integrated, patient-centered approach addresses the full spectrum of sensory, motor, cognitive, and psychological dimensions of vestibular dysfunction. As VRT continues to evolve, the synergy of technological innovation and neurophysiological insight offers a robust framework for improving long-term functional outcomes and quality of life in diverse vestibular populations.

Keywords: Sensory integration, Virtual reality, Telerehabilitation, Vestibular compensation, Persistent postural-perceptual dizziness

*** Corresponding author's e-mail:** muhammedceryilmaz@gmail.com

Cite as: Eryılmaz, M.C. (2026). Scientific and Technological Transformation in Vestibular Rehabilitation: Neurophysiology-Based, Personalized, and Integrated Approaches, *Journal of Innovative Healthcare Practices*, *7*(2),173-186. https://doi.org/10.58770/joinihp.1812996

Vestibüler Rehabilitasyonda Bilimsel ve Teknolojik Dönüşüm: Nörofizyolojik Temelli, Kişiselleştirilmiş ve Entegre Yaklaşımlar

ÖZET

Vestibüler rehabilitasyon tedavisi (VRT), mekanizma temelli, çok duyusal ve teknolojik olarak entegre bir modele doğru bir paradigma değişikliği geçirmektedir. Bu derleme, anlatısal (narrative) bir derleme niteliğinde olup bu dönüşüme ilişkin güncel kanıtları sentezlemeyi amaçlamaktadır. Bu dönüşüm, nörofizyoloji, tanı hassasiyeti ve sanal gerçeklik (VR) gibi sürükleyici teknolojilerdeki ilerlemeler tarafından yönlendirilmektedir ve bunlar toplu olarak kişiselleştirmeyi ve terapötik etkinliği artırmaktadır. Öncelikle periferik bozuklukları hedef alan geleneksel yaklaşımlar, artık özellikle Kalıcı Postural-Algısal Baş Dönmesi (PPPD) ve vestibüler migren gibi durumlarda, merkezi işleme bozuklukları, bilişsel-duygusal komorbiditeler ve uyumsuz duyusal entegrasyonu ele alan stratejilerle tamamlanmaktadır. VR tabanlı rehabilitasyon, duyusal girdilerin ve görev karmaşıklığının kontrollü bir şekilde manipülasyonunu mümkün kılarak, vestibüler kompansasyonun altında yatan temel nörofizyolojik mekanizmalar olan adaptasyon, alışma ve ikameyi kolaylaştırır. Video Baş İmpuls Testi (vHIT) ve Bilgisayarlı Dinamik Postürografi (CDP) gibi objektif tanı araçları, vestibülo-oküler refleks (VOR) fonksiyonu ve duyusal yeniden ağırlıklandırmanın bireyselleştirilmiş değerlendirmelerini sağlayarak hedefe yönelik müdahalelere rehberlik eder. Giyilebilir sensörler ve mobil platformlar, yüksek kaliteli VRT'yi ev ortamlarına da taşıyarak, gerçek zamanlı izleme ve geri bildirim yoluyla erişilebilirliği ve uyumu artırır. Randomize kontrollü çalışmalar ve meta-analizler, periferik ve merkezi vestibüler bozukluklarda VR tabanlı müdahalelerin klinik etkinliğini desteklemekte ve bazı çalışmalar geleneksel yöntemlere kıyasla benzer, seçilmiş hasta gruplarında ise potansiyel olarak daha iyi sonuçlar bildirmektedir. Önemli olarak, karmaşık vakaların yönetimi giderek fizik tedavi uzmanları, odyologlar, nörologlar ve ruh sağlığı uzmanları arasındaki disiplinler arası işbirliğine dayanmaktadır. Bu entegre, hasta merkezli yaklaşım, vestibüler disfonksiyonun duyusal, motor, bilişsel ve psikolojik boyutlarının tümünü ele almaktadır. VRT gelişmeye devam ederken, teknolojik yenilik ve nörofizyolojik içgörünün sinerjisi, çeşitli vestibüler popülasyonlarda uzun vadeli fonksiyonel sonuçları ve yaşam kalitesini iyileştirmek için sağlam bir çerçeve sunmaktadır.

Anahtar Kelimeler: Duyusal entegrasyon, Sanal gerçeklik, Telerehabilitasyon, Vestibüler kompansasyon, Kalıcı postural-algısal baş dönmesi

1 Introduction

Vestibular physical therapy is undergoing a significant transformation, moving away from traditional, symptom-driven paradigms toward a mechanistically grounded, multisensory rehabilitation model. This evolving framework is informed by advances in neurophysiology, enhanced diagnostic precision, and the integration of immersive technologies such as VR. Collectively, these innovations aim to personalize therapy and optimize functional outcomes in individuals with vestibular dysfunction (Tramontano et al., 2025; Fan et al., 2025; Kim, 2023; Liu et al., 2023; Abd-Elhamid et al., 2024).

Vestibular dysfunction represents a substantial and often underrecognized public health burden, frequently presenting as dizziness, imbalance, impaired gait, and heightened fall risk. These symptoms adversely affect quality of life and contribute to significant healthcare costs. Such dysfunction is a central feature in a range of conditions, including chronic disorders like PPPD, vestibular loss (VL), and post-stroke imbalance (Savitha et al., 2025; Marioni, 2022; Cochrane et al., 2021). VRT plays a critical role in mitigating these symptoms. Evidence supports its effectiveness in improving balance, gait stability, and dizziness severity across diverse populations, including individuals with peripheral vestibular pathologies, PPPD, and vestibular complications secondary to diabetes (Fan et al., 2025; Savitha et al., 2025; Abd-Elhamid et al., 2024; Tramontano et al., 2021). Additionally, the increasing recognition of cognitive and emotional comorbidities in vestibular disorders underscores the necessity for a comprehensive, multisensory approach to treatment (Smith et al., 2024; Wolfe et al., 2024; Ma et al., 2022; Dieterich & Brandt, 2023).

This shift in clinical perspective is further operationalized through the application of advanced diagnostic tools and immersive therapeutic modalities. VR-enhanced assessments such as Dynamic Visual Acuity (DVA) testing and Head Impulse Testing (HIT) provide objective, ecologically valid measures of VOR function and postural control, which are particularly valuable in diagnosing and monitoring complex syndromes like PPPD (Holford et al., 2022; Desoche et al., 2023; Nowakowski et al., 2023). In parallel, VR-based rehabilitation offers immersive, multisensory environments that can be tailored to challenge and train balance, gaze stabilization, and spatial cognition. These interventions have demonstrated favorable, and in some cases superior, outcomes compared to traditional VRT across a spectrum of conditions, including peripheral vestibular dysfunction, post-stroke imbalance, and PPPD (Abd-Elhamid et al., 2024; Surano et al., 2022; Kriz et al., 2024). When integrated with telehealth platforms, VR rehabilitation can also address long-standing barriers related to access, adherence, and healthcare costs, enhancing scalability and continuity of care (Perez-Heydrich et al., 2024).

This narrative review aims to discuss and summarize how advances in neurophysiological understanding and technological innovation are shaping contemporary VRT practices. Specifically, it discusses how approaches grounded in multisensory integration, objective diagnostics, and immersive therapy may more effectively target the complex sensory, cognitive, and emotional factors underlying chronic vestibular disorders. In doing so, this review seeks to summarize the current evidence regarding their potential to enhance the efficacy, accessibility, and personalization of vestibular care, while highlighting the methodological limitations of the existing literature.

2 Methods: Literature Search Strategy

This article is a narrative review and does not claim to follow a systematic review methodology. Accordingly, no formal PRISMA protocol, quantitative pooling of data, or formal appraisal of evidence certainty (e.g., GRADE) was performed. To enhance transparency and reproducibility, however, the literature search process is summarized below.

The PubMed, Scopus, Web of Science, and Google Scholar databases were searched for relevant English-language literature published between January 2020 and October 2025, with a small number of seminal earlier works included where required for conceptual background. The search combined terms related to the clinical domain and to the technological and neurophysiological focus of the review, using Boolean operators. Representative search strings included combinations of “vestibular rehabilitation” OR “vestibular physical therapy” AND (“virtual reality” OR “immersive technology” OR “telerehabilitation” OR “wearable sensors”), as well as (“vestibulo-ocular reflex” OR “video head impulse test” OR “computerized dynamic posturography” OR “sensory reweighting”) AND (“persistent postural-perceptual dizziness” OR “vestibular migraine” OR “functional dizziness”).

Peer-reviewed original studies, systematic reviews, meta-analyses, and authoritative clinical references relevant to the neurophysiology, assessment, technological enhancement, and clinical management of vestibular disorders were considered eligible. Priority was given to randomized controlled trials, systematic reviews, and meta-analyses, while smaller pilot studies and feasibility reports were included where higher-level evidence was unavailable and are identified as such in the text. Non-English sources, conference abstracts without full text, and studies not directly relevant to the review’s scope were generally excluded. Reference lists of key articles were also screened to identify additional relevant publications. Owing to the narrative design, study selection involved a degree of expert judgement rather than a formal screening algorithm, which is acknowledged as a limitation.

3 Advanced Diagnostic and Assessment Methods

The transition in VRT toward a mechanistically informed, multisensory framework is increasingly supported by advanced diagnostic technologies that enable precise, individualized interventions (Keshner et al., 2023; Tramontano et al., 2025). The vHIT offers real-time, objective assessment of high-frequency VOR function, quantifying VOR gain during rapid head movements. This tool is instrumental in distinguishing between acute and compensated vestibular lesions and in monitoring recovery trajectories (Nowakowski et al., 2023; Desoche et al., 2023). Similarly, CDP provides a quantitative analysis of postural control by identifying the balance strategies employed and evaluating how the central nervous system reweights sensory input from visual, somatosensory, and vestibular systems. These insights are crucial for targeting specific deficits in sensory integration (Brock et al., 2022; Soto-Varela et al., 2020). As summarized in Table 1, the integration of these diagnostic modalities within VR-based frameworks enhances ecological validity and enables precision rehabilitation through individualized, mechanism-driven interventions.

The integration of these diagnostic tools with VR further enhances ecological validity and enables precision rehabilitation by simulating real-world challenges within controlled, adaptive environments (Holford et al., 2022; Desoche et al., 2023). In the treatment of Benign Paroxysmal Positional Vertigo (BPPV), traditional maneuvers such as Epley and Semont remain effective for posterior canal involvement. However, recent clinical practice has shifted toward more canal-specific strategies, with maneuvers like the Gufoni and its adaptations being employed for horizontal canal variants, reflecting a more nuanced understanding of BPPV subtypes (Higashi-Shingai et al., 2023). Although BPPV is a mechanically driven, peripheral disorder treated primarily by repositioning rather than by technology-based rehabilitation, it is relevant to the present discussion in two respects: accurate canal-specific diagnosis increasingly benefits from instrumented and video-based assessment, and a subset of patients experience residual dizziness after successful repositioning that is amenable to the same mechanism-based, technology-assisted rehabilitation strategies described below.

Even after successful canalith repositioning, some patients experience residual dizziness, often linked to central sensitization rather than unresolved peripheral pathology (Tramontano et al., 2021; Holmberg, 2020). This underscores the need to supplement mechanical maneuvers with therapeutic interventions that address central processing particularly sensory reweighting and cognitive-motor integration. Such approaches align with evidence-based strategies used for conditions like Persistent Postural Perceptual Dizziness (PPPD), where lingering symptoms are driven by maladaptive central responses (Faúndez et al., 2025; Mempouo et al., 2021). VR-based rehabilitation serves as an effective modality for delivering structured multisensory training and controlled exposure to complex stimuli, thereby supporting desensitization and promoting central adaptation (Heffernan et al., 2021; Tramontano et al., 2025).

Table 1: *Neurophysiological Mechanisms Underpinning Contemporary Vestibular Rehabilitation Therapy*

Mechanism	Definition / Goal	Methods / Approaches	Neurophysiological Basis	Clinical Relevance	Key References
Adaptation	Recalibration of the VOR to improve gaze stability	Head and gaze stabilization exercises	Enhances VOR gain and dynamic visual acuity; relies on cerebellar learning mechanisms	Essential for improving visual stability during head movements, especially in unilateral vestibular hypofunction. Example: VOR×1/×2 gaze-stabilization exercises. Typical outcomes: DVA, VOR gain (vHIT), DHI.	Tramontano et al., 2025; Kim, 2023
Habituation	Reduction of dizziness through repeated exposure to provocative stimuli	Systematic exposure to motion or visual stimuli that provoke symptoms	Reduces central hyperexcitability; involves cortical desensitization and cerebellar modulation	Beneficial in cases of motion sensitivity and visually induced dizziness, such as in PPPD or vestibular migraine. Example: graded optokinetic/VR exposure, motion-provoking position drills. Typical outcomes: DHI, VVAS, SVV.	Tramontano et al., 2025; Tangniramai et al., 2024
Substitution	Compensation for lost or unreliable vestibular input via alternative sensory inputs	Sensory reweighting; multimodal balance training; increased use of visual and somatosensory cues	Enhances integration across parietal and cortical multisensory networks; promotes neuroplastic reorganization	Critical in bilateral vestibular loss or persistent vestibular dysfunction; supports functional mobility. Example: balance training on varied surfaces, somatosensory/visual-cue and gaze-substitution drills. Typical outcomes: CDP/SOT composite, gait speed, ABC scale.	Liu et al., 2023; Appiah-Kubi et al., 2024; Xavier et al., 2024

4 Management of Complex Vestibular Disorders

The evolving paradigm in VRT emphasizes mechanistically informed management of complex central vestibular disorders such as PPPD, Vestibular Migraine (VM), and functional dizziness (Waterston et al., 2021; Zamergrad et al., 2024). Although these conditions are frequently grouped together as central or functional disorders, they differ in their diagnostic criteria, underlying pathophysiology, and treatment response, and are therefore considered separately below.

Persistent Postural-Perceptual Dizziness (PPPD)

PPPD is increasingly understood through a biopsychosocial framework, wherein central sensory processing dysfunction, visual dependency, and postural control deficits are perpetuated by psychological and attentional factors, including anxiety and sensitivity to visual motion (Zamergrad et al., 2024; Zastenskaya & Antonenko, 2023). As a result, effective treatment extends beyond peripheral VRT, integrating habituation, graded sensory exposure, anxiety management, and cognitive-behavioral therapy (CBT) to reduce perceptual overload and central symptom amplification (Waterston et al., 2021; Zamergrad et al., 2024). In clinical practice, management typically combines four complementary elements: habituation training that systematically exposes the patient to provocative head and body movements; treatment of visual dependence through optokinetic or visually rich environments delivered in graded fashion; graded exposure to the situations the patient avoids, in order to interrupt the cycle of avoidance and symptom reinforcement; and CBT to address the anxiety and catastrophic appraisal that frequently sustain symptoms. VR-based interventions are particularly effective for this population, offering immersive environments for controlled exposure and cognitive-motor integration training (Harrell et al., 2022; Mempouo et al., 2021).

Vestibular Migraine (VM)

For VM, physical therapy serves as an adjunct to medical management, with tailored exercise protocols designed to improve balance, gaze stability, and sensory reweighting without triggering migrainous symptoms. Combined approaches that include vestibular adaptation and graded exposure, alongside migraine-specific strategies, have shown benefits in reducing dizziness-related disability (Batinović et al., 2024; Suparmin & Indriani, 2022; Lovato et al., 2023). Because VM is distinguished from PPPD by its episodic nature, its association with headache and other migrainous features, and its responsiveness to migraine-specific medical therapy, vestibular rehabilitation in this group is best positioned as a complementary rather than a stand-alone intervention. Trigger management (including sleep, hydration, and dietary factors) and pharmacological prophylaxis typically precede or accompany exercise, and exercise progression should be paced carefully to remain within the patient’s symptom tolerance, since overly aggressive provocation may precipitate attacks. Habituation and adaptation exercises are introduced gradually and titrated to the patient’s migraine threshold.

Functional Dizziness

Similarly, functional dizziness (also termed functional vertigo) is considered a disorder of central sensory integration. Multimodal treatment that combines VRT with CBT and anxiety reduction strategies has been shown to improve outcomes, particularly when focused on gradual environmental reconditioning and sensory desensitization (Zamergrad et al., 2024; Zastenskaya & Antonenko, 2023; Waterston et al., 2021). Because functional dizziness, PPPD, and VM share overlapping features yet differ in their diagnostic criteria and treatment emphasis, accurate differential diagnosis is a prerequisite for selecting the appropriate combination of vestibular, psychological, and, where indicated, pharmacological strategies.

Pediatric VRT: Special Considerations

Pediatric VRT presents unique challenges due to rapid developmental changes, comorbid hearing disorders, and differing attentional capacities (Baque et al., 2020; Peterson & Brodsky, 2022). Assessments must be developmentally appropriate and engaging, often requiring family-centered approaches and child-specific functional goals (Duarte et al., 2020). Because attention span, motivation, and the capacity to follow complex instructions vary with age, exercises are most effective when delivered through play-based and gamified formats that sustain engagement, and adherence depends heavily on active family participation, with caregivers trained to supervise and reinforce home practice. Immersive technologies should be introduced with particular caution in younger children, taking into account headset fit, visual maturation, and tolerance to sensory load. For pediatric VM, interventions should align with academic demands and cognitive load, gradually targeting visual-vestibular integration and balance control (Hayward et al., 2025; Tarnutzer & Kaski, 2023). In this context, telehealth and mobile health solutions are proving increasingly valuable for enhancing accessibility and continuity of care (Tee et al., 2022). An overview of the evolving VRT management strategies across these diagnostic categories is illustrated in Figure 1.

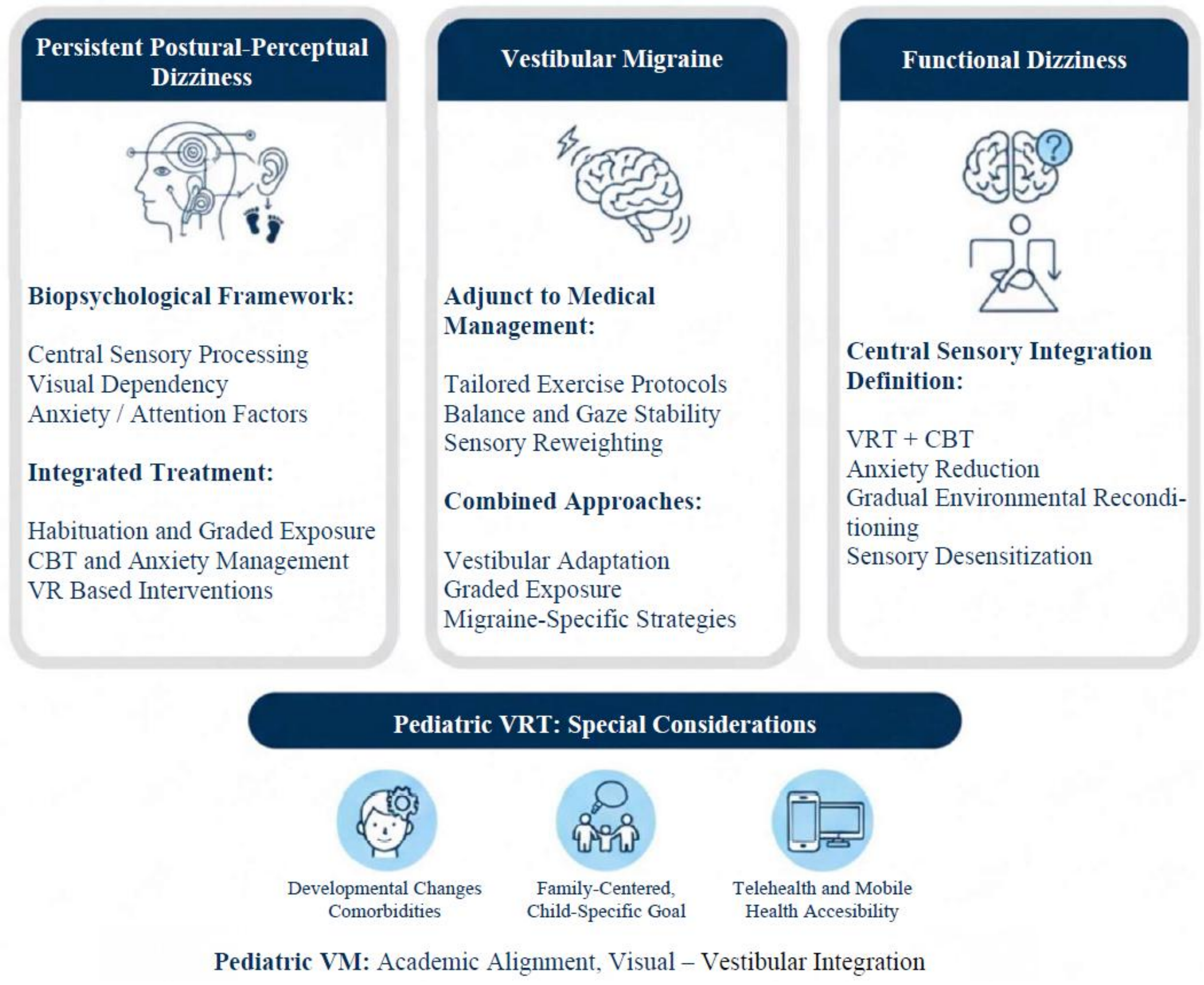

Figure 1. Overview of VRT strategies in PPPD, vestibular migraine, and functional dizziness. For each condition, the figure summarises the conceptual framework (left of each panel) and the corresponding integrated treatment components and outlines special considerations for pediatric VRT. PPPD: persistent postural-perceptual dizziness; CBT: cognitive-behavioral therapy; VR: virtual reality; VM: vestibular migraine.

5 Technologically Enhanced Vestibular Rehabilitation

Technologically enhanced VRT increasingly leverages VR, wearable sensors, and telerehabilitation to deliver mechanistically informed, multisensory, and accessible care (Eryılmaz, 2026c; Heffernan et al., 2023; Mempouo et al., 2021; Perez-Heydrich et al., 2024). As illustrated in Figure 2, these integrated technologies enable controlled manipulation of sensory conflict and task complexity to target key VRT mechanisms while supporting graded exposure for conditions such as PPPD. Moreover, wearable and mobile systems facilitate home-based rehabilitation through remote monitoring, individualized dosing, and objective feedback, whereas telerehabilitation enhances accessibility, continuity of care, and patient-centered delivery, demonstrating both feasibility and safety across diverse clinical populations. VR platforms offer distinct advantages over conventional methods by providing controlled environments that systematically manipulate sensory conflict and task complexity. This enables precise targeting of key neurophysiological mechanisms in VRT: adaptation through VOR gain recalibration, habituation via repeated exposure to symptom-provoking stimuli, and substitution through enhanced sensory reweighting (Nowakowski et al., 2023; Heffernan et al., 2023; Sana et al., 2023).

Figure 2. Technologically Enhanced Vestibular Rehabilitation: Mechanisms and Accessibility. The three panels depict complementary technological domains: virtual reality platforms (which manipulate controlled environments and sensory conflict to target VOR adaptation, habituation, substitution, and graded exposure for PPPD), wearable sensors and mobile health (supporting home-based rehabilitation, remote monitoring, individualized dosing, and adherence tracking), and telerehabilitation (enhancing accessibility, continuity, and patient-centered care while demonstrating feasibility and safety). VOR: vestibulo-ocular reflex; PPPD: persistent postural-perceptual dizziness.

Applications of VR in balance training have demonstrated comparable and in some studies potentially superior, efficacy to traditional VRT in improving postural stability and gait across vestibular and neurological populations (Sana et al., 2023; Sessoms et al., 2021). Importantly, VR enables the creation of graded exposure environments that are especially beneficial for patients with conditions such as PPPD, allowing systematic desensitization to visually complex or motion-rich stimuli in a safe and controlled setting (Mempouo et al., 2021; Park & Lee, 2023).

Wearable technology and mobile VR platforms facilitate the extension of high-fidelity rehabilitation into the home, enhancing accessibility and promoting patient-centered care (Perez-Heydrich et al., 2024). Remote monitoring via wearable sensors supports adherence tracking and individualized dosing, while studies confirm the feasibility and safety of home-based VRT programs (Tee et al., 2022; Perez-Heydrich et al., 2024). Real-time biofeedback from head-mounted displays and integrated motion sensors further anchor therapy in objective metrics, providing immediate feedback on gaze stabilization, posture, and movement quality for both patients and clinicians (Nowakowski et al., 2023; Brock et al., 2022).

6 Discussion

The ongoing shift in VRT toward a technologically enhanced, mechanistic model is increasingly supported by randomized controlled trials demonstrating its clinical efficacy (Sana et al., 2023; Heffernan et al., 2021). Comparative studies of VR-based and conventional VRT in populations such as individuals with subacute stroke and concussion report comparable, and in some cases potentially superior, outcomes in balance, gait, and dizziness reduction with VR interventions (Sessoms et al., 2021;

Sana et al., 2023). Meta-analyses further indicate that VR-enhanced VRT offers significant functional gains across both peripheral and central vestibular disorders, attributable to its immersive, multisensory environments, increased task complexity, and enhanced ecological validity (Hazzaa et al., 2023; Sana et al., 2023). The strength of this evidence, however, is not uniform across diagnoses. Relatively more consistent support exists for VR-based and conventional VRT in unilateral peripheral hypofunction and in PPPD, where graded visual-vestibular exposure has a clear mechanistic rationale, whereas the evidence base for vestibular migraine and for pediatric populations remains thinner and more heterogeneous. Moreover, several of the supporting trials are small-scale pilot or feasibility studies (e.g., Sessoms et al., 2021; Sana et al., 2023), characterised by limited sample sizes, heterogeneous populations, varied outcome measures, and short follow-up periods. These findings should therefore be interpreted with appropriate caution, and claims of superiority over conventional VRT remain provisional pending larger, adequately powered, and longer-term randomized controlled trials. VR is consequently best regarded at present as a promising complement to, rather than a replacement for, established vestibular rehabilitation, with patient selection (disorder type, symptom severity, susceptibility to visual provocation, and cognitive capacity) guiding its use.

Precision rehabilitation is facilitated by objective diagnostics that guide individualized intervention. The vHIT enables canal-specific quantification of high-frequency VOR responses, informing targeted gaze stabilization protocols. VR systems can provide real-time VOR biofeedback, further optimizing adaptive training (Nowakowski et al., 2023; Desoche et al., 2023). Likewise, CDP quantifies sensory weighting and balance strategies, offering data to personalize the sequencing and progression of sensory and motor challenges within the VR environment (Brock et al., 2022; Gawrońska et al., 2023). This integration allows therapy intensity, sensory conflict, and cognitive load to be calibrated according to each patient's functional and neurophysiological profile (Keshner et al., 2023; Holford et al., 2022). This diagnostic-driven model of individualization parallels a broader movement in rehabilitation medicine toward biologically and computationally informed personalization, in which genetic, epigenetic, and AI-derived indices are increasingly used to calibrate exercise dosage, progression, and feedback to the individual patient (Eryılmaz, 2026b).

The effective management of complex vestibular disorders increasingly relies on interdisciplinary collaboration. Physical therapists apply expertise in sensorimotor control and vestibular mechanisms, audiologists provide detailed vestibular diagnostics such as vHIT, and neurologists address central causes including VM and related comorbidities. Given the high prevalence of anxiety, fear-avoidance behavior, and cognitive-emotional dysfunction in conditions such as PPPD and chronic dizziness, the involvement of psychologists or mental health professionals is essential for comprehensive care (Waterston et al., 2021; Zamergrad et al., 2024).

Translating these tools into routine practice requires linking assessment findings to concrete intervention decisions. In principle, vHIT can identify the affected canal and the side and degree of VOR deficit, thereby directing the plane and intensity of gaze-stabilization (adaptation) exercises, while CDP can characterise which sensory channel a patient over- or under-relies upon, informing the sequencing of somatosensory- and visual-conflict conditions during sensory reweighting training. For PPPD, VR exposure is generally introduced at a low intensity of visual motion and advanced gradually as tolerance improves, whereas in vestibular migraine the same exposures are paced against the migraine threshold to avoid provocation. In telerehabilitation and home-based programmes, patient safety and fall prevention must be planned explicitly, for example through caregiver supervision, a safe exercise environment, and clear criteria for seeking in-person review, so that autonomy does not come at the expense of safety.

Limitations, Safety, and Implementation Challenges

Despite its promise, the technological transformation of VRT raises several practical and methodological challenges that temper the optimism of the current literature. First, immersive VR can itself provoke symptoms: visually induced motion sickness, or "simulator sickness" (nausea, disorientation, and visual fatigue), is a recognised adverse effect, which is particularly relevant in a population already sensitive to visual-vestibular conflict and which may limit tolerability or necessitate careful dose titration (Heffernan et al., 2021; Sana et al., 2023). Second, fall safety is a genuine concern when balance-challenging exercises are performed with a head-mounted display that restricts vision of the real environment, especially in older adults, for whom supervision, safe-environment set-up, and graded progression are essential (Soto-Varela et al., 2020; Tee et al., 2022).

Third, home-based and remote delivery, although it improves access and adherence, introduces challenges for clinical oversight: reduced direct supervision can make it harder to detect incorrect exercise performance, manage adverse responses promptly, and maintain engagement over time, so robust remote-monitoring and follow-up pathways are required (Perez-Heydrich et al., 2024; Kriz et al., 2024; Harrell et al., 2022). Fourth, wearable sensors and mobile platforms raise questions of data security, privacy, and measurement validity; clinical decisions based on consumer-grade devices require that the underlying metrics be adequately validated and that patient data be handled securely (Tee et al., 2022; Perez-Heydrich et al., 2024). These concerns parallel those raised in technology-supported neurorehabilitation, where unsupervised safety monitoring and robust data privacy/security protocols have similarly been identified as prerequisites for translating device-based interventions into sustainable, home-based care (Eryılmaz, 2026a). Fifth, the cost of VR hardware and instrumented assessment tools such as CDP, together with the need for clinician training and technical support, may constrain adoption, and these technologies risk widening disparities in care if they remain concentrated in well-resourced centres while access is limited in lower-resource settings (Keshner et al., 2023; Perez-Heydrich et al., 2024). Finally, in pediatric populations, attention, adherence, and the central role of family involvement further influence feasibility and outcomes (Baque et al., 2020; Duarte et al., 2020; Peterson & Brodsky, 2022). A formal evaluation of cost-effectiveness, against these benefits, was beyond the scope of this narrative review and represents an important direction for future health-economic research.

7 Conclusion

The transformation of VRT into a mechanistically driven, multisensory, and technologically integrated discipline reflects a broader commitment to precision, personalization, and evidence-based care. Grounded in neurophysiological principles and supported by objective diagnostics and immersive tools like VR, contemporary VRT now addresses not only peripheral deficits but also central processing dysfunctions and cognitive-emotional comorbidities. A growing body of randomized and clinical evidence supports the efficacy of this approach, with the most consistent benefits to date reported for unilateral peripheral hypofunction and for PPPD, where graded visual-vestibular exposure delivered through VR has a clear mechanistic rationale; the evidence for vestibular migraine and pediatric populations is more preliminary. Where measurable gains have been demonstrated, they have most often involved improvements in balance, gait stability, gaze stabilization, and dizziness-related disability, assessed with tools such as vHIT, CDP, and validated dizziness and balance outcome measures. Importantly, much of the supporting evidence derives from small pilot studies with short follow-up, so current conclusions remain provisional. As interdisciplinary collaboration deepens and technology continues to enhance access and adaptability, this evolving paradigm holds promise for improving functional outcomes and quality of life in individuals with vestibular dysfunction, provided that its adoption is matched by attention to safety, cost, and equitable access. Future research should prioritise larger, adequately powered, multicentre randomized controlled trials with longer-term follow-up; the definition of optimal VR dose-response parameters (intensity, frequency, and duration of exposure); the identification of which patient subgroups benefit most; and health-economic evaluation of cost-effectiveness and real-world implementation, including in lower-resource and pediatric settings.

8 Declarations

Acknowledgements

There is no person or institution contributing to this research other than the authors.

Funding source

No financial support was received for this study.

Competing Interests

The authors have no conflicts of interest to declare.

Authors' Contributions

Muhammed Celal ERYILMAZ served as the lead author in this review article, playing a pivotal role in the research process. He was instrumental in generating innovative ideas and hypotheses that guided the study's focus. ERYILMAZ meticulously planned the framework for the literature review, ensuring a comprehensive analysis of existing studies to establish a solid foundation for the research. He organized and synthesized the findings from the reviewed literature, presenting them in a clear and accessible manner.

9 Human and Animal Related Study

If the work does not involve the use of human/animal subjects, each manuscript should contain the following subheadings:

Ethical Approval

This study exclusively utilizes publicly available data obtained from open web platforms and, as such, is deemed exempt from formal ethical review processes. However, the research methodology was carefully designed to adhere to the principles of ethical research conduct, respecting the privacy and confidentiality of the data sources.

Informed Consent

There was no need for informed consent form to be obtained from participants for the study that they agreed to participate in the study.

References

Abd-Elhamid, E., Hazzaa, N., Manzour, A., & Galal, E. (2024). Efficacy of virtual reality as vestibular rehabilitative therapy in peripheral vestibular dysfunction: a systematic review and meta-analysis. QJM, 117(Supplement_1).

Appiah-Kubi, K., Galgon, A., Tierney, R., Lauer, R., & Wright, W. (2024). Concurrent vestibular activation and postural training recalibrate somatosensory, vestibular and gaze stabilization processes. Plos One, 19(7), e0292200. https://doi.org/10.1371/journal.pone.0292200

Baque, E., Jones, T., & Bialocerkowski, A. (2020). A survey of pediatric competencies in entry-level physical therapy programs in australia. Pediatric Physical Therapy, 32(4), 356-365. https://doi.org/10.1097/pep.0000000000000730

Batinović, F., Sunara, D., Košta, V., Pernat, M., Mastelić, T., Paladin, I., … & Đogaš, Z. (2024). Psychiatric comorbidities and quality of life in patients with vestibular migraine and migraine without vertigo: a cross-sectional study from a tertiary clinic. Audiology Research, 14(5), 778-789. https://doi.org/10.3390/audiolres14050065

Brock, C., Carmona, S., & Hochhegger, B. (2022). Analysis of body balance assessment results at posturography: an integrative review. Journal of Otolaryngology-Ent Research, 14(3), 62-68. https://doi.org/10.15406/joentr.2022.14.00508

Cochrane, G., Christy, J., & Motl, R. (2021). Central vestibular functions correlate with fatigue and walking capacity in people with multiple sclerosis. Physical Therapy, 101(9). https://doi.org/10.1093/ptj/pzab168

Desoche, C., Verdelet, G., Salemme, R., Farné, A., Pélisson, D., Froment, C., … & Hermann, R. (2023). Virtual reality set-up for studying vestibular function during head impulse test. Frontiers in Neurology, 14. https://doi.org/10.3389/fneur.2023.1151515

Dieterich, M. and Brandt, T. (2023). Central vestibular networking for sensorimotor control, cognition, and emotion. Current Opinion in Neurology, 37(1), 74-82. https://doi.org/10.1097/wco.0000000000001233

Duarte, J., Leão, E., Fragano, D., Marquez, G., Pires, A., Silva, M., … & Ganança, F. (2020). Vestibular syndromes in childhood and adolescence. International Archives of Otorhinolaryngology, 24(04), e477-e481. https://doi.org/10.1055/s-0039-3402443

Eryilmaz, M. C. (2026a). Integrated Technologies in Neurorehabilitation: Evidence, Mechanisms, and Future Perspectives. Abant Journal of Health Sciences and Technologies, 6(1), 72-85. https://izlik.org/JA62DP44FR

Eryilmaz, M. C. (2026b). Integration of Genetic, Epigenetic and Artificial Intelligence-Based Biomarkers in Personalized Exercise Prescription. Türkiye Sağlık Bilimleri ve Araştırmaları Dergisi, 9(1), 14-28. https://doi.org/10.51536/tusbad.1817230

Eryılmaz, M. C. (2026c). Telemedicine-Based Rehabilitation: Evidence, Applications and Innovative Technologies. Eurasian Journal of Health Technology Assessment, 10(1), 61-78. https://doi.org/10.52148/ehta.1846798

Fan, H., Ding, Y., Elmadhoun, A., Mangal, R., Feng, J., & Geng, X. (2025). Vestibular rehabilitation in patients with stroke: a comprehensive review of past and current evidence. Brain Circulation, 11(2), 107-112. https://doi.org/10.4103/bc.bc_16_23

Faúndez, F., Arévalo-Romero, C., Villarroel, K., Lavín, C., P., K., Vial, G., … & Breinbauer, H. (2025). Spatial navigation entropy suggests allocentric dysfunction in pppd. Frontiers in Neurology, 16. https://doi.org/10.3389/fneur.2025.1599307

Gawrońska, A., Rosiak, O., Pajor, A., Janc, M., Kotas, R., Kamiński, M., … & Józefowicz-Korczyńska, M. (2023). Instrumental and non-instrumental measurements in patients with peripheral vestibular dysfunctions. Sensors, 23(4), 1994. https://doi.org/10.3390/s23041994

Harrell, R., Schubert, M., Oxborough, S., & Whitney, S. (2022). Vestibular rehabilitation telehealth during the saea-cov-2 (covid-19) pandemic. Frontiers in Neurology, 12. https://doi.org/10.3389/fneur.2021.781482

Hayward, A., Farrell, L., & Sweeney, J. (2025). Physical therapy management of vestibular migraine of childhood: a case report. Pediatric Physical Therapy, 37(4), 495-504. https://doi.org/10.1097/pep.0000000000001230

Hazzaa, N., Manzour, A., Yahia, E., & Galal, E. (2023). Effectiveness of virtual reality-based programs as vestibular rehabilitative therapy in peripheral vestibular dysfunction: a meta-analysis. European Archives of Oto-Rhino-Laryngology, 280(7), 3075-3086. https://doi.org/10.1007/s00405-023-07911-3

Heffernan, A., Abdelmalek, M., & Nunez, D. (2021). Virtual and augmented reality in the vestibular rehabilitation of peripheral vestibular disorders: systematic review and meta-analysis. Scientific Reports, 11(1). https://doi.org/10.1038/s41598-021-97370-9

Heffernan, A., Booth, L., Fletcher, R., & Nunez, D. (2023). Vestibular rehabilitation potential of commercially available virtual reality video games. Journal of Otolaryngology - Head and Neck Surgery, 52(1). https://doi.org/10.1186/s40463-023-00642-9

Higashi-Shingai, K., Imai, T., & Inohara, H. (2023). 外側半規管型良性発作性頭位めまい症に対する耳石置換法. Equilibrium Research, 82(2), 68-76. https://doi.org/10.3757/jser.82.68

Holford, K., Jagodinsky, A., Saripalle, R., & McAllister, P. (2022). Leveraging virtual reality for vestibular testing: clinical outcomes from tests of dynamic visual acuity. Journal of Vestibular Research, 32(1), 15-20. https://doi.org/10.3233/ves-200782

Holmberg, J. (2020). Pathophysiology, differential diagnosis, and management of persistent postural-perceptual dizziness: a review. Perspectives of the Asha Special Interest Groups, 5(1), 181-191. https://doi.org/10.1044/2019_persp-19-00105

Keshner, E., Mallinson, A., Longridge, N., Sinno, S., Petersen, H., & Perrin, P. (2023). Evolution of postural control assessment: from dynamic posturography to virtual reality. Frontiers in Neurology, 13. https://doi.org/10.3389/fneur.2022.1054346

Kim, J. (2023). Neurophysiology of vestibular compensation. Audiology and Speech Research, 19(1), 1-16. https://doi.org/10.21848/asr.220082

Kriz, M., Conover, S., Cameron, N., Conover, M., Simon, J., Prueter, J., … & Backous, D. (2024). Comparing in-clinic versus telehealth for vestibular physical therapy. Journal of Vestibular Research, 34(4), 215-222. https://doi.org/10.3233/ves-220094

Liu, B., Shan, J., & Gu, Y. (2023). Temporal and spatial properties of vestibular signals for perception of self-motion. Frontiers in Neurology, 14. https://doi.org/10.3389/fneur.2023.1266513

Lovato, A., Disco, C., Frosolini, A., Monzani, D., & Perini, F. (2023). Monoclonal antibodies targeting cgrp: a novel treatment in vestibular migraine. Medicina, 59(9), 1560. https://doi.org/10.3390/medicina59091560

Ma, L., Marshall, P., & Wright, W. (2022). The impact of external and internal focus of attention on visual dependence and eeg alpha oscillations during postural control. Journal of Neuroengineering and Rehabilitation, 19(1). https://doi.org/10.1186/s12984-022-01059-7

Marioni, G. (2022). Vestibular rehabilitation for unilateral peripheral vestibular deficits. Jama Otolaryngology–head & Neck Surgery, 148(5), 434. https://doi.org/10.1001/jamaoto.2022.0158

Mempouo, E., Lau, K., Green, F., Bowes, C., & Ray, J. (2021). Customised vestibular rehabilitation with the addition of virtual reality based therapy in the management of persistent postural-perceptual dizziness. The Journal of Laryngology & Otology, 135(10), 887-891. https://doi.org/10.1017/s0022215121002127

Nowakowski, J., Moksud, N., & Zatoński, T. (2023). Eye tracking by virtual reality head mounted display provides biofeedback for gaze stabilisation exercises and enables on-the-fly measurement of vestibulo-ocular reflex gain. [Preprint]. Research Square. https://doi.org/10.21203/rs.3.rs-2871153/v1

Park, G. and Lee, H. (2023). Development and usability evaluation of a virtual reality-based vestibular rehabilitation system for balance enhancement. Journal of the Korean Society of Physical Medicine, 18(4), 155-162. https://doi.org/10.13066/kspm.2023.18.4.155

Perez-Heydrich, C., Creary-Miller, I., Spann, M., & Agrawal, Y. (2024). Remote delivery of vestibular rehabilitation for vestibular dysfunction: a systematic review. Otology & Neurotology, 45(6), 608-618. https://doi.org/10.1097/mao.0000000000004218

Peterson, J. and Brodsky, J. (2022). Evaluation and management of paediatric vertigo. Current Opinion in Otolaryngology & Head & Neck Surgery, 30(6), 431-437. https://doi.org/10.1097/moo.0000000000000849

Sana, V., Ghous, M., Kashif, M., Albalwi, A., Muneer, R., & Zia, M. (2023). Effects of vestibular rehabilitation therapy versus virtual reality on balance, dizziness, and gait in patients with subacute stroke: a randomized controlled trial. Medicine, 102(24), e33203. https://doi.org/10.1097/md.0000000000033203

Savitha, S., Kirthiga, A., & Sathishwari, S. (2025). Effectiveness of vestibular rehabilitation for diabetic patients in improving balance and quality of life. International Journal of Current Science Research and Review, 08(05). https://doi.org/10.47191/ijcsrr/v8-i5-28

Sessoms, P., Fraser, J., Bodell, D., Haluch, K., Markham, A., Brookfield, J., … & Gottshall, K. (2021). Clinical effectiveness of virtual reality versus conventional clinic-based vestibular physical therapy on balance and function in active duty service members. a pilot randomized controlled trial. Virtual Reality, 27(1), 263-276. https://doi.org/10.1007/s10055-021-00546-x

Smith, L., Wilkinson, D., Bodani, M., & Surenthiran, S. (2024). Cognition in vestibular disorders: state of the field, challenges, and priorities for the future. Frontiers in Neurology, 15. https://doi.org/10.3389/fneur.2024.1159174

Soto-Varela, A., Rossi-Izquierdo, M., del-Río-Valeiras, M., Vaamonde-Sánchez-Andrade, I., Faraldo-García, A., Lirola-Delgado, A., … & Santos-Pérez, S. (2020). vestibular rehabilitation using posturographic system in elderly patients with postural instability: can the number of sessions be reduced?. Clinical Interventions in Aging, Volume 15, 991-1001. https://doi.org/10.2147/cia.s263302

Suparmin, N. and Indriani, I. (2022). Effectiveness of vertigo rehabilitation exercise, dizziness and balance disorders (vdb) in elderly : narrative review. Jurnal Kesehatan Mesencephalon, 8(1). https://doi.org/10.36053/mesencephalon.v8i1.312

Surano, S., Grip, H., Öhberg, F., Karlsson, M., Faergemann, E., Bjurman, M., … & Salzer, J. (2022). Internet-based vestibular rehabilitation versus standard care after acute onset vertigo: a study protocol for a randomized controlled trial. Trials, 23(1). https://doi.org/10.1186/s13063-022-06460-0

Tangniramai, O., Chunwaree, O., & Kingrat, I. (2024). Physical therapy with cawthorne-cooksey exercise for reducing the risk of falling in older people with dizziness from vestibular hypofunction. Siriraj Medical Bulletin, 17(2), 137-145. https://doi.org/10.33192/smb.v17i2.265768

Tarnutzer, A. and Kaski, D. (2023). What’s in a name? chronic vestibular migraine or persistent postural perceptual dizziness?. Brain Sciences, 13(12), 1692. https://doi.org/10.3390/brainsci13121692

Tee, L., Seah, W., Chia, C., Neoh, E., Lim, P., Liaw, S., … & Ho, E. (2022). Development and feasibility of a mobile-based vestibular rehabilitation therapy application for healthy older adults. Annals of the Academy of Medicine Singapore, 51(8), 514-516. https://doi.org/10.47102/annals-acadmedsg.202213

Tramontano, M., Haijoub, S., Lacour, M., & Manzari, L. (2025). Updated views on vestibular physical therapy for patients with vestibular disorders. Healthcare, 13(5), 492. https://doi.org/10.3390/healthcare13050492

Tramontano, M., Princi, A., Angelis, S., Indovina, I., & Manzari, L. (2021). Vestibular rehabilitation in patients with persistent postural-perceptual dizziness. Hearing Balance and Communication, 19(4), 282-290. https://doi.org/10.1080/21695717.2021.1975986

Waterston, J., Chen, L., Mahony, K., Gencarelli, J., & Stuart, G. (2021). Persistent postural-perceptual dizziness: precipitating conditions, co-morbidities and treatment with cognitive behavioral therapy. Frontiers in Neurology, 12. https://doi.org/10.3389/fneur.2021.795516

Wolfe, J., Levi, D., Holt, L., Bartoshuk, L., Herz, R., Klatzky, R., … & Merfeld, D. (2024). Vestibular sensation.. https://doi.org/10.1093/hesc/9780197663813.003.0013

Xavier, F., Chouin, E., Tighilet, B., Chabbert, C., & Besnard, S. (2024). Innovative approaches for managing patients with chronic vestibular disorders: follow-up indicators and predictive markers for studying the vestibular error signal. Frontiers in Rehabilitation Sciences, 5. https://doi.org/10.3389/fresc.2024.1414198

Zastenskaya, E. and Antonenko, L. (2023). Comorbid disorders and therapy of persistent postural perceptual dizziness. Neurology Neuropsychiatry Psychosomatics, 15(4), 66-73. https://doi.org/10.14412/2074-2711-2023-466-73

Zamergrad, M., Parfenov, V., Ostroumova, O., Guseva, A., Zaytseva, O., Sivolap, Y., … & Voronov, V. (2024). Functional dizziness: from diagnostic criteria to clinical profiles and therapy. expert consensus. Neurology Neuropsychiatry Psychosomatics, 16(4), 4-13. https://doi.org/10.14412/2074-2711-2024-4-4-13