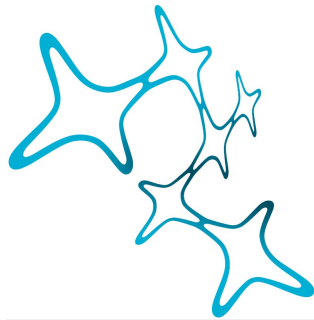
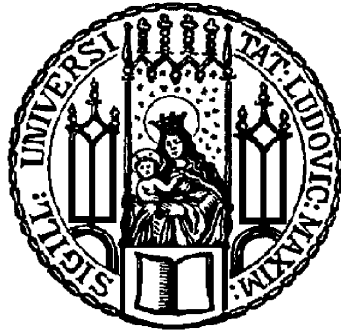


**Innovations in Visual Rehabilitation:  
Novel Therapeutic Approaches for Homonymous  
Visual Field Defects**

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## Summary

Visual field loss resulting from stroke and other types of brain injury is prevalent yet often overlooked. This impairment significantly impacts key aspects of daily life, including reading and visual exploration, ultimately diminishing independence and quality of life. Current rehabilitative strategies for visual field loss adopt different approaches: some utilize optical aids, others aim to restore visual sensitivity through repeated stimulation of the blind field, and a third group—compensatory training—seeks to improve visual function by training patients to make better use of their intact visual field, primarily through enhanced eye movement strategies. The latter approach shows the greatest promise to date. However, important limitations persist, including limited ecological validity and modest functional transfer across different tasks.

The overarching aim of this dissertation is to address these gaps by developing and evaluating novel compensatory training methods that are more ecologically valid and functionally comprehensive. Two empirical studies were conducted to pursue this goal, each targeting distinct limitations in existing compensatory interventions. In the first study, we examined the feasibility and effectiveness of a fully home-based, therapist-independent visual exploration training program using Virtual Reality in patients with homonymous visual field defects. This approach aimed to overcome the spatial constraints of conventional screen-based training by enabling users to explore a broader visual field and incorporate head movements, better simulating real-world visual behavior. The findings indicated high levels of adherence and patient acceptability, along with significant enhancements in visual search performance following completion of all training phases. In the second study, we addressed the problem of task specificity by evaluating a novel training protocol that combined elements of visual exploration and reading. Conducted with healthy participants with simulated hemianopia, this study aimed to assess whether exploration training that integrates text-based components would lead to broader functional benefits compared to exploration training without text-based elements. Results demonstrated that, while both the combined and the exploration-only training used in this study led to significant improvements in visual exploration and reading, the integrated approach produced superior gains in reading performance. These outcomes suggest that combining reading with exploration training enhances the functional transfer of skills across domains.

In addition to the empirical findings, practical and methodological considerations encountered during the research process are also examined in this dissertation, including the challenges of selecting appropriate control conditions and experimental designs to accurately evaluate the effects of intervention programs.

Overall, this work advances the field of visual rehabilitation by presenting evidence for the feasibility and effectiveness of more ecologically valid and functionally transferable compensatory training strategies. It highlights the benefits of incorporating broader visual environments and head movements, as well as integrating task-relevant content to produce more robust and generalizable improvements in patients with visual field deficits.

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## 1. General Introduction

### 1.1. Homonymous visual field deficits

Despite their underrecognition, visual problems are alarmingly common in acute stroke, affecting over half of all survivors (Rowe et al., 2019). Among these, visual field defects are particularly prevalent, with estimates suggesting that between 20% and 57% of individuals experience some degree of visual field loss following a stroke (Pollock et al., 2012). Within this group, homonymous visual field defects (HVFDs) emerge as the most common type of visual field impairment after brain injury (Rowe et al., 2013). HVFDs are impairments that affect the same side of the visual field in both eyes, resulting from lesions in the post-chiasmal visual pathways (Zihl, 2010; Zihl & Kennard, 2003; Goodwin, 2014). Due to the crossing of nasal retinal fibers at the optic chiasm, this type of damage leads to contralateral visual field loss (Zihl, 2003). HVFDs manifest in various forms depending on the size and location of the lesion (see *Figure 1* for a schematic overview), including hemianopia (loss of one visual hemifield), quadrantanopia (loss of one quadrant), and scotoma (localized areas of vision loss) (Zihl & Kennard, 2003). Among these, homonymous hemianopia is the most prevalent (Rowe et al., 2013).

Although stroke, especially ischemic or hemorrhagic events involving the posterior cerebral artery, is the leading cause of HVFDs, accounting for up to 70% of cases (Goodwin, 2014; Rowe et al., 2009; Pambakian et al., 2005; Zhang et al., 2006a), these impairments can also result from a variety of other conditions, including tumors and traumatic brain injuries (Zhang et al., 2006a). Age plays a significant role in both the prevalence and etiology of HVFDs. In adults, these visual field defects are considerably more common, primarily due to vascular diseases, which are becoming increasingly prevalent with age. Conversely, HVFDs are relatively rare in children and adolescents, where they are more often linked to traumatic brain injuries and tumors (Goodwin, 2014; Kedar et al., 2006).

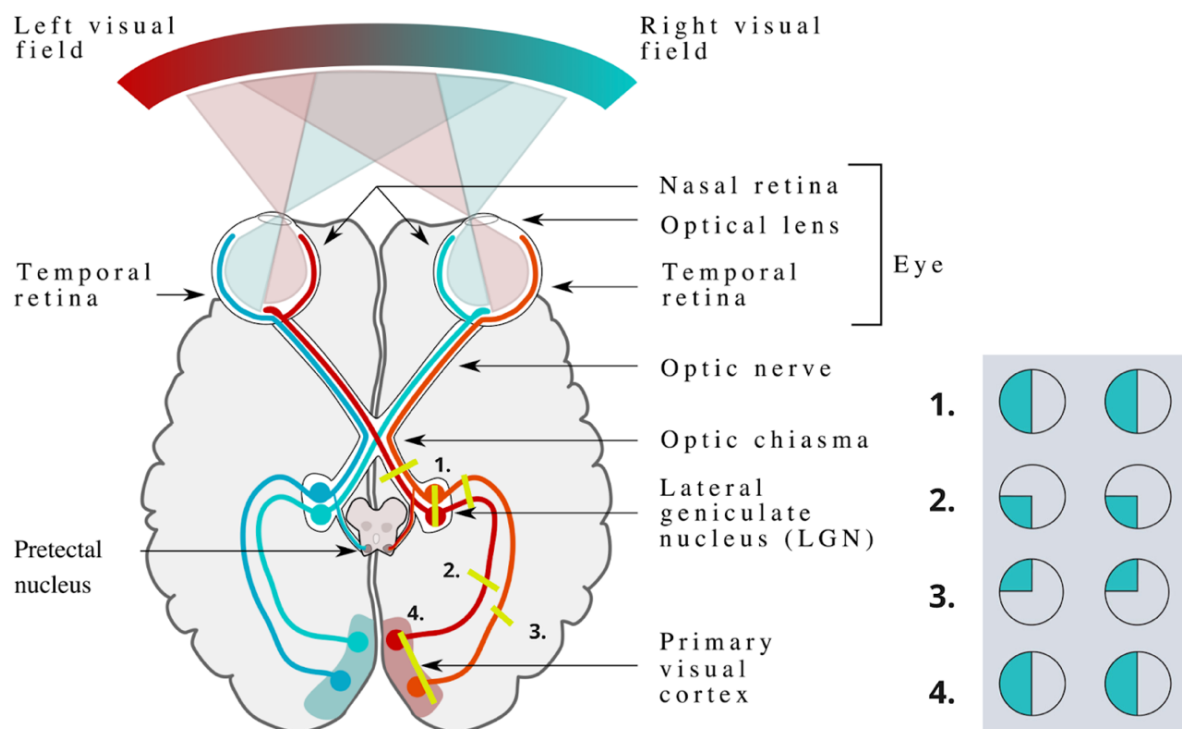
### 1.2. Impairments caused by HVFDs

Given the complex and varied causes of HVFDs, the prognosis can be challenging. While some patients may experience spontaneous recovery, the overall outlook for HVFDs remains poor. Most improvement occurs within the first month after injury, and by six months, only 10–20% of individuals show measurable recovery (Zihl, 2010; Zhang et al., 2006b). For individuals who do not experience spontaneous recovery, HVFDs lead to significant impairments that severely affect daily functioning. These deficits hinder spatial awareness, reading, navigation, and visual exploration, which in turn diminish social participation and overall quality of life (Gall et al., 2009). They also elevate the risk of depression and social isolation (Goodwin, 2014; Jones & Shinton, 2006). Furthermore, these impairments increase the likelihood of injury, disorientation, falls, and difficulty recognizing hazards,

particularly when driving or crossing streets (de Haan et al., 2015a; Goodwin, 2014). A major factor contributing to the described impairments in HVFDs is disrupted oculomotor scanning, which impairs eye movement patterns during visual exploration. Compared to healthy controls, individuals with homonymous hemianopia show longer search times, more fixations, smaller saccadic amplitudes, and inefficient search paths (Machner et al., 2009; Pambakian et al., 2000; Zihl, 1995a, 1999). Gaze distribution is also often altered. Pambakian and colleagues (2000) found that patients made smaller saccades toward the blind field compared to the sighted field, resulting in longer scanpaths compared to control participants.

**Figure 1**

*Schematic view of the visual pathway with post-chiasmal lesions leading to homonymous visual field deficits*



*Note.* (1) A complete lesion affecting the right optic tract, lateral geniculate nucleus, or optic radiations leads to a complete loss of the left visual field in both eyes, i.e. left homonymous hemianopia. (2) Damage to the right upper optic radiations results in a loss of vision in the lower left quadrant of the visual field (left inferior quadrantanopia). (3) Damage to the right lower optic radiations leads to a visual deficit in the upper left quadrant (left superior quadrantanopia). (4) A lesion of both the superior and inferior right optic radiations in the primary visual cortex also results in left homonymous hemianopia. The illustration is adapted from an original by Miquel Perello Nieto. The original image is licensed under the terms of the Creative Commons Attribution-ShareAlike 4.0 International License (CC BY-SA 4.0) and is available at Wikimedia Commons.

Some patients with HVFDs spontaneously develop compensatory oculomotor strategies. Zihl (1995a) found that 40% of patients exhibited visual search patterns similar to those of healthy individuals, while Fellrath and Ptak (2015) observed that some patients utilized distributed fixations in a manner akin to healthy controls during natural scene viewing. However, the extent to which this spontaneous compensation is effective and long-lasting remains unclear. Reinhard et al. (2014) argued that long-term adaptation is insufficient, as they found no correlation between reduced saccadic accuracy and disease duration. Machner et al. (2009) observed that only one of nine patients maintained significant improvement in visual search patterns, such as fewer saccades and more structured search paths, after an 18-month follow-up. These findings suggest that while compensatory oculomotor strategies may develop in some patients, their persistence over time is limited.

While most research on visual exploration impairments in HVFDs has focused on eye movements, head movements also play a critical role and are similarly affected. Unlike eye movements, head movements are more complex and require longer programming time, which may lead patients to adopt simpler exploration strategies that minimize head involvement, relying more heavily on eye movements instead (Schoepf & Zangemeister, 1993; Zangemeister et al., 1982). When head movements are employed, they often show increased latency toward the blind hemifield and may follow a “staircase” pattern, mirroring the small, stepwise saccades observed in oculomotor behavior of patients with HVFDs (Zangemeister et al., 1982). In real-world tasks such as driving, Bowers and colleagues (2014) found that although individuals with homonymous hemianopia made more head scans toward their blind side at intersections than controls, the scans were of smaller magnitude, resulting in reduced pedestrian detection. Thus, impairments in head movement contribute to the overall inefficiency of visual exploration in HVFDs and may further compromise safety.

Reading impairments are particularly challenging due to the structured, directional nature of reading, which allows for fewer compensatory strategies than general visual exploration. Efficient reading relies on precise oculomotor control, with rapid saccades spanning 7–9 letters interspersed with fixations that enable word recognition and comprehension (Rayner, 1998; Schotter et al., 2012). Even small central scotomas can disrupt this process, as foveal and parafoveal vision are critical for fluent reading (Trauzettel-Klosinski, 2002). Macular sparing—preserved central vision within 1° to 10° of the visual field—can mitigate some difficulties, but extensive sparing is rare; about 75% of patients retain less than 4° (Horton et al., 2021; Leff, 2004; Schuett et al., 2008a). Sparing of 5° or more is typically needed for unimpaired reading (Trauzettel-Klosinski & Reinhard, 1998). Reading direction also influences the type and the extent of impairments. In left-to-right scripts, right-sided hemianopia causes more severe impairments because the perceptual span processed in a given fixation lies

predominantly in the right visual field (Goodwin, 2014; Leff et al., 2000; Schuett, 2009; Trauzettel-Klosinski, 2002; Zihl, 1995b). This condition, known as hemianopic alexia, leads to slow reading, shorter saccades, increased fixations and regressions, and errors such as omissions or incorrect word guesses (Leff et al., 2006; McDonald et al., 2006; Trauzettel-Klosinski, 2002). In contrast, left-sided hemianopia mainly disrupts line transitions and has less impact on reading fluency overall (McDonald et al., 2006; Zihl, 1995b). Overall, the presence of HVFDs can affect reading speed, accuracy, and ultimately, quality of life and social participation (Leff & Behrmann, 2008; Maeyama et al., 2024).

### *1.3. Diagnosis of HVFDs and differentiation from spatial neglect*

The diagnosis of HVFDs relies primarily on perimetry, a clinical method for measuring the extent of the visual field. Two main types of perimetry are used: static perimetry, which presents fixed stimuli of varying luminance at set locations, and kinetic perimetry, which involves moving a stimulus from a non-seeing area into the visual field until it is detected by the patient (Wall, 2021). Automated static perimetry, such as that performed with the Humphrey Field Analyzer or Octopus perimeters, is the standard diagnostic tool for HVFDs (Goodwin, 2014). Advances in computer-based perimetric technologies have further improved the process by enhancing comfort, shortening testing time, and increasing validity and reliability (Jariyakosol et al., 2021).

However, diagnosing HVFDs can be complicated by their clinical similarity to spatial neglect—a neuropsychological syndrome that typically arises from right hemisphere damage, particularly in the parietal lobe or temporo-parietal junction, and is marked by a failure to attend or respond to stimuli in the contralesional space (Li & Malhotra, 2015). Because both HVFDs and neglect patients may omit targets in the affected visual field, standard perimetry can produce similar-looking results for both conditions. This overlap poses a diagnostic challenge for HVFDs, especially in patients with co-occurring parietal lesions, which can disrupt both the attentional systems involved in neglect and the optic radiation responsible for HVFDs (Karnath, 2001). Differentiating between the two is essential, as the mechanisms and rehabilitation approaches can differ. Experimental manipulations during visual testing can aid differentiation. For instance, modifying perimetry by briefly removing the fixation cross before target onset can help distinguish neglect from HVFDs (Walker et al., 1991).

In addition to producing similar perimetry results, both conditions also share oculomotor abnormalities, such as hypometric saccades toward the affected field and an increased number of fixations during visual search tasks (Pambakian et al., 2000; Sprenger et al., 2002; Walle et al., 2019). Yet, important differences in exploratory behavior can help distinguish the two. In neglect, patients show a persistent ipsilesional bias, with the center of attention and gaze shifted toward the unaffected

side (Karnath et al., 1998). In contrast, individuals with isolated HVFDs tend to develop compensatory gaze strategies, shifting their visual exploration toward the blind side (Ishiai et al., 1987; Zihl et al., 2009). Fellrath and Ptak (2015) further confirmed this by showing that during natural scene viewing, only patients with both neglect and HVFDs exhibited a horizontal gaze shift, whereas those with HVFDs alone did not show this pattern. The time course of recovery further distinguishes the two. In the acute phase, HVFDs may also show an ipsilesional bias, but this often reverses through spontaneous adaptation as patients learn to compensate (Saj et al., 2012). In contrast, neglect patients typically do not develop compensatory strategies, and the ipsilesional bias persists chronically.

In summary, while both HVFDs and spatial neglect involve deficits in the contralesional space, they differ in underlying mechanisms, behavioral manifestations, and patterns of compensation. In patients presenting with both conditions, neglect symptoms tend to dominate, potentially masking the more subtle compensatory strategies seen in HVFDs. Accurate diagnosis thus requires not only perimetry but also a nuanced assessment of attentional biases and eye movement behavior.

#### *1.4. Current rehabilitation approaches for HVFDs*

Rehabilitation strategies for HVFDs generally fall into three categories: substitution using optical aids, visual restitution, and compensatory training. Optical substitution uses prism glasses to shift visual input from the blind side to the seeing retina. Peripheral prisms, often mounted above and below the line of sight, can expand the visual field by 20–30° (Goodwin, 2014; Peli, 2000). More advanced oblique prism designs offer greater central field expansion, potentially aiding tasks like driving (Bowers et al., 2012), although they reduce lateral coverage. Newer models aim to balance wider lateral field expansion with the need for effective scanning (Peli et al., 2016). While early results are encouraging, robust randomized controlled trials are still missing. While optical aids like prism glasses can significantly enhance obstacle detection and navigation safety (Giorgi et al., 2009), long-term adherence remains a challenge, with less than half of patients continuing use after 12 months (Bowers et al., 2008), often due to discomfort. As a result, they are frequently used in combination with eye movement training or visual restitution therapies to provide a more comprehensive and sustainable rehabilitation strategy (Schofield & Leff, 2009)

Restorative training, such as Visual Restoration Therapy (VRT), attempts to recover visual field function through repetitive stimulation with light stimuli at the border of the blind area. Early studies claimed long-lasting gains (Kasten & Sabel, 1995), but these findings were later challenged due to poor fixation control (Horton, 2005). More rigorously controlled studies have found minimal improvements (Lane et al., 2008), calling into question the clinical utility of traditional VRT. In contrast, motion perception

training in patients with primary visual cortex damage—where several surviving extrastriate visual pathways may mediate residual, often unconscious functions known as "blindsight"—has shown promising results, with evidence of improved motion discrimination in the blind field (Huxlin et al., 2009; Ajina et al., 2021). These findings indicate that adults may have a much greater ability for visual plasticity after primary visual cortex damage than previously thought. However, the durability and functional relevance of these improvements remain uncertain.

Compensatory training currently represents the most evidence-based and effective approach for managing HVFDs, showing consistent improvements in visual exploration (Howard & Rowe, 2018; Kerkhoff, 2000; Lane et al., 2008; Pollock et al., 2019). These interventions train patients to optimize their remaining vision by adopting strategic eye movements, particularly by directing saccades into the blind field and making larger saccades, thereby enhancing visual scanning (Kerkhoff, 2000; Pambakian et al., 2005; Pelak et al., 2007). Multisensory exploration strategies, such as combining visual tasks with auditory cues, may enhance outcomes even further (Keller & Lefin-Rank, 2010). Training typically involves daily one-hour sessions over four weeks, during which patients complete visual search tasks using eye movements alone (Lane et al., 2008). This method has been shown to significantly improve search speed, reduce errors, and expand the visual search area, with effects visible after as few as 4–8 sessions (Kerkhoff et al., 1992; Pambakian et al., 2004; Zihl, 1995a). Patients with coexisting neglect need about 25% more training to reach comparable outcomes (Kerkhoff et al., 1992). While the visual field itself is not restored with eye movement training, gains in functional vision tend to be durable (Bouwmeester et al., 2007; Mannan et al., 2010; Pelak et al., 2007).

Compensatory training for visual exploration and reading is usually delivered through distinct, specialized programs. Reading-focused training aims to improve oculomotor skills specific to reading by fine-tuning saccadic behavior and often involves presenting text-based stimuli for a limited amount of time (Aimola et al., 2014; Schuett et al., 2012; Zihl, 1995b; Zihl et al., 2021). These interventions enhance visual attention and improve fixation precision, saccadic amplitude, and reading speed (Maeyama et al., 2024; Zihl, 1995b). Patients with both left- and right-sided HVFDs benefit, right-sided cases, however, typically require more intensive training (Kerkhoff, 2000; Zihl, 1995b).

While these outcomes are encouraging, the effectiveness of compensatory approaches also depends on several additional factors. Generally, successful compensatory training relies on both the patients' awareness of their deficit and their active engagement (Kerkhoff & Schenk, 2012). However, this presents a challenge in HVFD rehabilitation, as post-stroke anosognosia—particularly in patients with co-occurring neglect—can impede progress (Jenkinson et al., 2011). Highlighting this issue, Rowe and colleagues (2013) reported that 16% of individuals with visual field loss were unaware of their

condition, underscoring the need for clinicians to actively assess and address awareness levels when designing interventions.

### *1.5. Gaps in current compensatory rehabilitation approaches*

Compensatory visual exploration training stands out as a relatively effective intervention for HVFDs; however, its scope and impact remain limited in several critical areas. A central concern in computerized compensatory rehabilitation, particularly visual exploration and scanning training, is the inconsistent transfer of training benefits to activities of daily living (ADL).

Visual exploration therapy is a well-established intervention not just for HVFDs, but also for spatial neglect (Cicerone et al., 2000; Cicerone et al., 2019), yet evidence supporting its generalizability to ADL remains sparse and inconclusive (Bowen et al., 2013; Cicerone et al., 2019). For instance, Schröder and colleagues (2008) reported lack of transfer from visual exploration training to functional domains such as reading, writing, or standard neglect assessments. The combination of visual exploration training with therapies such as neck muscle vibration (Schindler et al., 2002) or optokinetic stimulation (Schröder et al., 2008), however, appears to enhance generalization.

It might be tempting to assume that since visual exploration impairments are more profound in neglect than in HVFDs, the generalization of visual exploration training could be more effective for the latter group. However, despite some indications that HVFD patients respond better to such training (Kerkhoff et al., 1992; Szalados et al., 2021), the extension of training effects to functional activities remains unreliable. Findings from Aimola and colleagues (2014) further complicate this picture, as they observed that patient-reported benefits did not translate into measurable gains in simulated ADL tasks, raising doubts about the extent to which visual exploration training truly enhances functional autonomy.

Similar task-specificity concerns are evident when exploring transfer between visual search and reading performance. Research has demonstrated that improvements in one domain rarely translate to the other. Exploration training tends to enhance search efficiency without benefiting reading, whereas reading-specific interventions improve reading skills without enhancing exploration capabilities (Lane et al., 2010; Schuett et al., 2012; Zihl et al., 2021; Postuma et al., 2024). This likely stems from the fundamentally different oculomotor demands of these tasks: reading requires precise, small-scale horizontal saccades, while exploration depends on broader, multi-directional eye movements (Aimola et al., 2014; Schuett et al., 2012).

Another significant limitation lies in the unclear long-term efficacy of compensatory training approaches. Although some studies suggest durability of treatment effects, the evidence is mixed. For example, Pambakian and colleagues (2004) reported improvements in visual search following saccadic training that were maintained one month post-training. Zihl and colleagues (2021) found that improvements in scanning performance persisted for up to five years post-treatment. However, not all findings are as optimistic. De Haan et al. (2016) observed that while patients reported long-term benefits, objective testing did not conclusively support these claims. The study recommended periodic refresher sessions to preserve acquired skills, highlighting the potential fragility of compensatory gains over time.

Beyond efficacy concerns, practical and methodological limitations also hinder the broader application of compensatory training. Most exploration-based interventions are location-specific and require supervision by trained therapists in clinical settings, making them resource-intensive and less accessible. Aimola et al. (2014) initiated investigations into home-based training alternatives, demonstrating encouraging results in both reading and visual exploration tasks. However, further research is needed to substantiate and expand upon these findings.

Another practical limitation—potentially contributing to the restricted generalization of training effects—is the inherently artificial nature of conventional computer-based compensatory rehabilitation programs. These training programs often use abstract stimuli (e.g., shapes or lines), which bear little resemblance to real-world scenarios such as locating items in a crowded supermarket. In contrast, Mena-Garcia et al. (2021) addressed this issue with a non-computerized multitasking compensatory saccadic training program that employed three-dimensional, real-world objects. This regimen, combining in-office and customized home-based sessions over 12 weeks, produced meaningful improvements in visual functioning, quality of life, and functional independence, suggesting that rehabilitation strategies grounded in ecologically valid settings may offer greater benefits than traditional screen-based methods.

Finally, technical limitations of computer-based training further constrain its generalizability. The spatial constraints of standard monitors restrict the range of eye movements that can be practiced, focusing predominantly on saccadic training while neglecting the role of head movements—an essential component of real-world visual exploration. This oversight may further limit the transferability of learned skills to complex, dynamic environments typical of daily living.

### *1.6. Objectives of the dissertation*

While existing compensatory exploration training programs have demonstrated effectiveness, it is clear that there remains significant room for improvement, especially in making these interventions more accessible, ecologically valid, and functionally transferable. The overarching objective of this dissertation is to address several critical gaps in current compensatory rehabilitation approaches for individuals with HVFDs.

One of the focal areas of this work is to explore home-based, therapist-independent training solutions that overcome the logistical and spatial limitations of traditional computer-based programs. Current interventions are often constrained by fixed screen dimensions, which restrict the range of eye movements that can be trained and largely neglect head movements—an essential component of real-world visual exploration. Furthermore, standard compensatory training is highly task-specific, with limited evidence supporting the transfer of skills from exploration exercises to other vital functions such as reading. By targeting these shortcomings, we aim to contribute to the design of more versatile, user-friendly, and generalizable compensatory training programs. We address these shortcomings through two complementary studies, each approaching the shortcomings from a different, but related, angle.

The first study investigates the feasibility and efficacy of a fully home-based, therapist-independent visual exploration training program delivered through virtual reality (VR). By leveraging VR technology in this study, we aim to overcome the spatial constraints of conventional screen-based training by enabling patients to explore a larger visual field and to incorporate head movements, thereby closer approximating the demands of real-world visual exploration behavior.

Despite the growing interest in VR applications within neurorehabilitation, research specifically addressing its use in compensatory training for HVFDs remains limited. Existing studies have primarily examined the use of VR in the context of audiovisual stimulation, cognitive rehabilitation, or restitutive therapies for patients with HVFDs. For instance, Daibert-Nido et al. (2021) implemented an audiovisual 3D-Multiple Object Tracking paradigm using VR in two pediatric hemianopia patients, demonstrating both feasibility and the potential for improvements in visual perception and quality of life. Misawa et al. (2024) extended this approach to a greater number of hemianopic children and adolescents, reporting high adherence, minimal side effects, and sustained functional improvements over six months. While all participants completed the visual training with minimal technical issues or cybersickness, many found the training repetitive and suggested personalization or gamification to

enhance engagement (Tchao et al., 2024). In the context of cognitive rehabilitation, Dehn et al. (2020) implemented a VR-based shopping task as part of a 14-day intervention. This approach not only enhanced performance on the trained task itself but also led to broader improvements in related neuropsychological domains, including visual memory, visuoconstructive abilities, and cognitive flexibility. In the domain of restitutive therapies, Namgung et al. (2024) conducted a double-blind randomized controlled trial evaluating a VR-based visual perceptual learning program. Over a 12-week period, stroke patients engaged in tasks involving orientation, rotation, and depth discrimination using a head-mounted VR device. The intervention resulted in significant gains in luminance detection sensitivity within the affected hemifield, as assessed by the Humphrey visual field test.

Studies that specifically evaluate the efficacy of VR-based compensatory training for HVFDs, particularly in terms of functional visual outcomes, are scarce. Most existing literature emphasizes feasibility, usability, and user experience rather than direct rehabilitation outcomes. For instance, Gestefeld et al. (2020) incorporated commonly used mobility-related vision exercises into a VR format using a head-mounted display; patients reported a positive user experience, highlighting the practicality of such an approach. Similarly, Knobel et al. (2021) developed an immersive visual search task for patients with hemispatial neglect, who rated the VR game as highly engaging and motivating. Although their study targeted a different clinical population, the underlying methodological framework offers avenues for adaptation to HVFD rehabilitation.

In summary, although existing research highlights the promise and acceptability of VR-based interventions in visual and cognitive rehabilitation, it remains unclear whether these approaches can produce clinically meaningful improvements in compensatory behavior for individuals with HVFDs. To begin addressing this gap, we evaluated both the feasibility and efficacy of a home-based VR visual search training program for patients with HVFDs. By replacing standard computer monitors with head-mounted displays (HMDs), we created a more immersive environment that allows for the stimulation of a significantly larger visual field. The integration of rotational tracking technology enabled us to manipulate visual content based on head orientation, facilitating two distinct training modes. In the eye movement training (EMT) format, rotational tracking was disabled, and the display remained static regardless of head movements, isolating eye movement strategies. In contrast, tracking was activated in the head movement training (HMT) format, allowing participants to reveal new parts of the virtual environment through head movements. We assessed the effects of these training formats on oculomotor behavior and performance in visual search and, complimentary, reading tasks. Patients with HVFDs progressed through three sequential four-week training phases, with outcome assessments conducted at baseline, between phases, and post-intervention. The first phase served as

a placebo condition, with stimuli restricted to the intact visual field. The second phase introduced EMT, with stimuli distributed across both hemifields but without dynamic visual updates. The third phase implemented HMT, requiring participants to explore a wider virtual space using both eye and head movements. While this study provided important insights into the effects of different VR-based training modes, its design did not allow us to fully address the issue of task specificity that often limits the generalizability of conventional compensatory training. To this end, we conducted a separate study.

With the second study, we addressed the issue of task specificity in compensatory training by investigating whether a novel, combined compensatory training approach, integrating elements of both visual exploration and reading, could produce functional improvements in both areas. While both abilities are essential for ADL, previous research (see 1.5. *Gaps in current compensatory rehabilitation approaches*) has shown that traditional training methods tend to yield task-specific effects—visual exploration training improves search performance without benefiting reading, and vice versa. Consequently, most interventions have targeted these skills in isolation, with little expectation of transfer effects. One notable exception is the study by Aimola and colleagues (2014), which combined exploration and reading exercises within a single intervention. Their results indicated improvements in both domains, though the individual contributions of each component remained unclear. Building on this work, we evaluated a unified training paradigm for individuals with simulated hemianopia. Unlike conventional methods, this approach used a single task format designed to concurrently enhance both reading and exploration performance, aiming to deliver a more efficient and cost-effective therapeutic option. The computer-based training was developed for independent use at home, without the need for direct clinical supervision. Involving healthy participants with simulated visual field loss allowed to isolate the effects of visual field loss from potential comorbidities, while also allowing for a larger sample size to generate preliminary data. The primary goal was to assess whether the combined training yielded superior improvements in both reading and exploration tasks compared to an exploration-only training program.

Together, these studies aim to contribute to the advancement of neurovisual rehabilitation by promoting compensatory training strategies that are not only effective but also flexible, scalable, and grounded in real-world applicability. A central thread uniting both studies is their shared focus on improving visual function through the modulation of oculomotor behavior, which is a key indicator of functional vision in individuals with HVFDs. Moreover, both studies prioritize accessibility and engagement by exploring novel training platforms and formats. The first study evaluates the efficacy and feasibility of a home-based VR program, offering a promising alternative to conventional screen-

based interventions by enabling larger-scale visual field exploration and the inclusion of head movements. The second study, although conducted in a controlled laboratory environment, presents a training approach that combines visual exploration with reading tasks, aiming to optimize transfer effects across functions while minimizing the need for separate, time-intensive therapies. This integrative design reflects a more resource-efficient and potentially scalable direction for rehabilitation.

With this dissertation that incorporates innovative delivery methods and cross-functional training designs, we aim to contribute to the development of rehabilitation interventions that are clinically meaningful, widely accessible, and better aligned with the everyday needs of individuals living with HVFDs. Ultimately, these efforts are directed toward improving the practical utility, ecological validity, and real-world impact of compensatory therapies, supporting greater independence and quality of life for those affected.

## 2. Manuscripts

### I. Exploring New Frontiers in VR-Based Visual Rehabilitation for Patients with Homonymous Visual Field Deficits

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## **Abstract**

Homonymous visual field deficits (HVFDs) can profoundly impact visual exploration and reading, necessitating effective rehabilitative interventions. Traditional compensatory scanning training has shown promise in enhancing visual search strategies, yet its implementation has largely been confined to PC-based programs. Virtual reality (VR) offers a compelling alternative, providing an engaging training environment while enabling exploration of a larger visual field. This study aimed to assess the feasibility and efficacy of a home-based VR visual search training program for individuals with HVFDs. Participants completed three sequential training phases over 12 weeks: a placebo phase, an eye movement training (EMT) phase, and a head movement training (HMT) phase. Visual search performance was evaluated using five key measures: search time, number of saccades, saccadic amplitude, percentage of first saccades into the blind field, and saccadic asymmetry.

Contrary to expectations, EMT alone did not yield statistically significant improvements compared to the placebo phase, nor did the addition of HMT result in further enhancements in visual search outcomes. However, when considering the combined effects of EMT and HMT relative to the placebo phase, significant improvements emerged in search time and the number of saccades, with a trend toward a higher percentage of first saccades directed into the blind field. Interestingly, the placebo training itself appeared to influence search performance, potentially masking the subsequent benefits of EMT and HMT. These findings suggest that the order of training phases and adaptations from placebo training may have affected overall efficacy, underscoring the importance of carefully selecting control conditions. The small sample size limited definitive conclusions regarding reading performance, though descriptive data revealed trends aligned with known lateralization effects in HVFDs.

Despite these limitations, the study highlights the feasibility and acceptability of VR-based rehabilitation for individuals with HVFDs. Adherence rates were high, and the VR environment's ability to engage larger portions of the visual field underscores its potential for broader clinical application. These findings add to the growing body of evidence supporting compensatory training and demonstrate VR's promise as an accessible and effective rehabilitation tool. Future research should aim to optimize training protocols and assess VR-based interventions in real-world contexts to further validate their clinical utility.

## **Introduction**

### ***Homonymous Visual Field Defects: Causes and Impacts***

Homonymous visual field defects (HVFDs) are visual impairments that affect the same side of the visual field in both eyes, resulting from lesions in the post-chiasmal visual pathways (Zihl, 2010; Zihl & Kennard, 2003). The severity and type of HVFD can vary significantly depending on the size and location of the lesion, with common forms including hemianopia (loss of one visual hemifield), quadrantanopia (loss of one quadrant), and scotoma (a small, localized area of vision loss) (Zihl & Kennard, 2003). The most frequent cause of HVFDs is ischemic or hemorrhagic stroke affecting the posterior cerebral artery, accounting for roughly 70% of cases, though other etiologies such as subarachnoid hemorrhage, intracerebral hematomas, brain injuries, tumors, and, more rarely, demyelinating diseases, brain surgery, and congenital conditions can also contribute (Zhang et al., 2006a). Despite the potential for some spontaneous recovery, HVFDs often have a poor prognosis, with only 10-20% of patients experiencing improvement within 3-6 months post-injury (Zihl, 2010). The probability of recovery is greatest within the first month after injury and drops to approximately 20% by six months (Zhang et al., 2006b).

A distinctive feature of HVFDs is macular sparing, where central vision remains intact despite the presence of a visual field defect (Leff, 2004). Although macular sparing helps preserve central vision, HVFDs still severely impact daily life. Individuals with HVFDs may struggle to perform essential tasks such as reading, driving, and navigating their environment, particularly due to difficulty detecting objects in their impaired visual field. These visual limitations can lead to disorientation, an increased risk of falls, challenges when crossing streets, and trouble identifying hazards, all of which compromise safety and independence (de Haan, Heutink, et al., 2015; Goodwin, 2014).

One key factor contributing to these difficulties is the disruption of oculomotor scanning behavior during visual exploration and search. HVFDs significantly impair eye movement patterns, leading to disorganized scanning not only within the affected hemifield but also, to a lesser extent, in the intact visual field (Zihl, 1995a). These disruptions manifest as longer search times, an increased number of saccades and fixations, smaller saccadic amplitudes, and inefficient, often repetitive scanpaths (Machner et al., 2009; Pambakian et al., 2000; Zihl, 1995a, 1999). Visual exploration tends to be laborious, characterized by small, hypometric saccades toward the blind field—a strategy known as the “staircase” approach, which, while safe, can be time-consuming (Pambakian et al., 2000; Zihl, 1995a). Over time, some patients adapt by adopting a more efficient “overshoot” strategy, where a

large saccade overshoots the search target, followed by a minor corrective movement (Meienberg, 1988; Meienberg et al., 1981).

The distribution of gaze can also be affected in HVFDs. Patients often make more saccades toward the blind hemifield, though these are typically less accurate and systematic, contributing to prolonged search times (Zihl, 1995a). Pambakian et al. (2000) observed that patients not only spent a greater proportion of their total fixation time in their blind field but also made saccades into this area with shorter latencies and smaller amplitudes compared to saccades directed toward the sighted hemifield, leading to longer overall scanpaths than those of control participants. However, not all patients with HVFDs exhibit these oculomotor impairments. Zihl (1995a) found that around 40% of patients displayed visual search patterns comparable to those of healthy individuals. Similarly, Fellrath and Ptak (2015) observed that, during natural scene viewing, some patients with hemianopia distributed fixations and utilized visual saliency cues in ways similar to healthy controls. Thus, while HVFDs generally lead to inefficient visual exploration and disordered oculomotor strategies, the severity and nature of these impairments can vary significantly between individuals.

HVFDs not only disrupt eye movements but also influence head movement patterns during visual exploration and task performance. Several studies have reported that in patients with HVFDs the proportion of the movement amplitude covered by moving the head in combined head-eye movements is smaller than in healthy controls. This is possibly due to the increased complexity and time required to program head movements compared to eye movements (Schoepf & Zangemeister, 1993; Zangemeister et al., 1982). This can result in a preference for simpler strategies that minimize or even eliminate head movements, with patients relying more heavily on eye movements (Zangemeister et al., 1982). When head movements do occur, they often show increased latency, particularly when turning toward the blind hemifield, and may follow a “staircase” pattern similar to the hypometric saccades observed in eye movement studies (Zangemeister et al., 1982).

Other research suggests that head movement strategies can vary depending on the task. For example, Hardiess et al. (2010) found that during a comparative visual task involving object recognition and memory, HVFD patients demonstrated head movement amplitudes comparable to or even exceeding those of healthy controls, suggesting task-specific compensatory strategies. Similarly, in driving studies, head movements play a crucial compensatory role. Wood et al. (2011) observed that drivers with hemianopia or quadrantanopia made more head movements toward their blind side, particularly those rated as safe to drive, indicating that increased head scanning may help maintain driving safety. Yet, the effectiveness of these compensations might not always be sufficient. Bowers et al. (2014) found that while drivers with homonymous hemianopia performed more head scans toward the blind

side at intersections compared to controls, the magnitude of these scans was smaller, leading to more failures in pedestrian detection tasks. Together, these findings highlight the complexity and variability of head movement adaptations in HVFDs, influenced by individual differences and task demands.

The compensatory strategies observed in tasks like visual search and driving illustrate how individuals with HVFDs adapt to manage visual field loss. These tasks often allow for flexible adjustments, such as increased head movements, to compensate for impaired vision. However, reading presents unique challenges that limit such adaptations. It relies on parafoveal vision and precise eye movements—elements that head movements cannot easily substitute.

Reading impairments in patients with HVFDs are heavily influenced by both the side and extent of the visual field loss. Parafoveal vision, which supports saccade planning and enables readers to preview upcoming words, is essential for fluent reading. As a result, the degree of macular sparing in HVFDs plays a critical role in preserving reading ability. Patients with 3°–5° of macular sparing typically experience only mild reading difficulties (Papageorgiou et al., 2007), while sparing beyond 5° is generally necessary for unimpaired reading performance (Trauzettel-Klosinski & Reinhard, 1998). Unfortunately, such extensive macular sparing is uncommon, with around 75% of patients having less than 4° of preserved central vision (Schuett et al., 2008b), which limits their capacity to effectively utilize parafoveal information during reading.

For left-to-right readers, right homonymous hemianopia presents a particularly significant challenge, as the visual field loss affects the area where upcoming text appears. Patients often struggle to locate subsequent words and make systematic saccades, resulting in disorganized eye movement patterns marked by prolonged fixations, reduced saccadic amplitudes, and an increased number of regressive saccades (Zihl, 1995b). Severe right hemianopia has also been associated with disruptions in the neural systems responsible for the motor planning of reading saccades, impairing both the preparation and execution of these eye movements (Leff et al., 2000). This pattern of reading impairment, known as “hemianopic alexia,” shares features with pure alexia, including a pronounced word-length effect, where reading times increase proportionally with word length (Sheldon et al., 2012).

While left homonymous hemianopia generally results in less severe reading impairments for left-to-right readers, it still presents challenges. Patients often struggle to find the beginning of new lines, as the return sweep—a saccade that moves the eyes from the end of one line to the start of the next—must extend into the blind visual field. This can result in inaccurate saccades, requiring additional corrective backward eye movements to properly align with the new line. Such disruptions hinder the smooth progression of reading, leading to a slower pace and increased effort (Zihl, 1995b).

### ***Hemianopia rehabilitation methods***

The above information section described how HVFDs can significantly impact daily life, making routine tasks more challenging. Rehabilitation strategies aim to enhance visual performance and help patients adapt to field loss. Three main approaches are commonly mentioned in literature: optical aids, visual restoration training (VRT), and compensatory training. These methods can be customized and combined to address individual patient needs, optimizing functional outcomes.

Optical aids, such as prism glasses, aim to artificially expand a patient's visual field. Peripheral prism segments, typically positioned above and below the line of sight on spectacle lenses, shift images from the blind hemianopic side to the seeing retina, effectively broadening the visual field by 20° to 30° (Goodwin, 2014; Peli, 2000). Oblique prisms, set at 30° angles, offer even greater central field expansion. Research has demonstrated that these prisms can significantly improve hazard detection while driving, potentially enabling patients with complete hemianopia to meet legal driving standards (Bowers et al., 2012; Goodwin, 2014). However, this design reduces the extent of lateral field expansion compared to traditional horizontal prisms. To compensate, stronger prisms may be used. Researchers are exploring different optical designs to maximize lateral expansion while also considering other factors like blind spots created by the prisms and the patient's ability to scan their environment effectively (Peli et al., 2016). Such prisms designs are promising, but randomized controlled trials focusing on evaluating the clinical potential and functional outcomes of this rehabilitation technique are still missing, although there are some promising early results with a randomized controlled multi-center trial being currently conducted (Peli et al., 2024).

VRT aims to restore parts of the lost visual field through prolonged, structured training. Patients focus on a central fixation point while stimuli, typically light targets, are presented along the border between their seeing and blind fields during daily one-hour sessions over six months (Kasten & Sabel, 1995; Kasten et al., 1997). Placebo-controlled studies suggested lasting improvements, particularly in cases involving optic nerve damage (Kasten et al., 1998, 2000, 2001). However, subsequent research criticized these findings due to inadequate fixation control (Horton, 2005; McFadzean, 2006). Later studies with more precise fixation monitoring found no significant visual field improvements, and the modest 1.8° increase reported by Kasten et al. (2006) was considered clinically insignificant given the time and cost of the therapy (Lane et al., 2008); similarly, a review by Pollock et al. (2011) concluded that light-target stimulation does not reliably expand the sighted field.

While traditional VRT has shown limited success, approaches focusing on improving sensitivity to specific stimuli, such as motion, have demonstrated promise. Studies have demonstrated enhanced

motion discrimination in HVFD patients (Huxlin et al., 2009; Cavanaugh et al., 2019; Vaina et al., 2014) and even sighted field expansion (Ajina et al., 2021; Cavanaugh & Huxlin, 2017). Nonetheless, questions remain regarding the long-term persistence of these benefits and their impact on activities of daily living (ADLs).

A complementary approach involves multisensory training, which combines auditory and visual stimuli to enhance visual sensitivity. Bolognini et al. (2005) found that two weeks of audiovisual stimulation improved visual detection and oculomotor exploration in eight chronic HVFD patients, with effects lasting a month. More recently, Rowland et al. (2023) reported similar gains in two post-stroke patients. Nahum and Ptak (2023) introduced adapted boxing therapy, integrating physical, occupational, and neuropsychological training, which improved spatial awareness and visual function in a stroke patient with hemianopia and visuospatial neglect after six months of therapy. While promising, these findings are based on small samples and require further validation.

In contrast to restorative approaches, compensatory training targets the use of remaining vision by teaching patients effective eye movement strategies to compensate for visual field loss. Since many HVFD patients do not naturally develop efficient compensatory behaviors (Kerkhoff, 1999; Postuma et al., 2023), this type of training aims to correct disorganized saccades into the blind hemifield, helping patients enhance visual exploration. This method, regarded as the most studied and potentially effective rehabilitation approach (Lane et al., 2008; Pelak et al., 2007), typically involves daily one-hour sessions over four weeks (Lane et al., 2008). Patients are instructed to rely solely on eye movements rather than head movements, focusing on directing saccades into the blind field and practicing larger saccadic movements to improve visual scanning speed and efficiency (Kerkhoff, 2000; Pambakian et al., 2005; Pelak et al., 2007). As training progresses, these strategies can be reinforced through real-life applications.

Compensatory training has been shown to significantly improve visual search performance, with faster response times, fewer errors, more efficient saccades, and an expanded visual search field (Kerkhoff et al., 1992; Pambakian et al., 2004; Zihl, 1995a). Improvements can be observed after as few as 4–8 sessions, although patients with neglect typically require 25% more training to achieve similar outcomes (Kerkhoff et al., 1992). Importantly, compensatory training not only enhances visual search abilities but also positively impacts ADLs, as evidenced by empirical assessments and patient-reported outcomes (Nelles et al., 2001; Pambakian et al., 2004). As research continues to refine compensatory strategies, biofeedback training (BT) has emerged as a promising new approach. Traditionally used for central vision loss, BT has recently been adapted for homonymous hemianopia. Misawa et al. (2023) employed a microperimeter with audio feedback to shift the locus of fixation toward the seeing

hemifield, leading to improvements in visual function, including reading speed and contrast sensitivity, in 9 out of 11 patients. While promising, further research is needed to validate its effectiveness.

Despite its numerous benefits, compensatory training faces several challenges, including the lack of standardized methodologies (Pelak et al., 2007) and limited high-quality evidence regarding its impact on quality of life (Pollock et al., 2019). However, a systematic review by Postuma et al. (2024) noted that, although performance-enhancing scanning behaviors—such as reduced fixations and shorter scan paths—tend to be task-specific, current compensatory scanning training programs are capable of inducing such behaviors.

In addition to general visual scanning training, compensatory reading programs have been developed to address reading difficulties in patients with HVFDs by optimizing saccadic eye movements to improve reading efficiency (Tol et al., 2024). These programs often involve training patients to adjust their gaze toward the blind hemifield and practice larger, more efficient saccades through techniques such as brief word or sentence presentations (Aimola et al., 2014; Schuett et al., 2012; Zihl, 1995b; Zihl et al., 2021). A recent study by Kerkhoff & Kraft (2024) proposed a novel reading training for hemianopic alexia that combines three different methods (floating text, rapid serial visual presentation of single words, and the moving window technique), which led to significant and lasting improvements in reading performance and reduced symptom load. Approximately 63% of patients returned to work after therapy, highlighting its potential for meaningful rehabilitation. Numerous other studies have demonstrated that compensatory reading training improves reading speed, reduces errors, and enhances oculomotor control, characterized by fewer and shorter fixations, while promoting larger saccades (Aimola et al., 2014; Maeyama et al., 2024; Zihl, 1995b; Zihl et al., 2021). Patients with right-sided hemianopia often require more training sessions than those with left-sided hemianopia to achieve similar improvements, yet these interventions still lead to lasting benefits (Kerkhoff, 1999, 2000; Zihl et al., 2021). Regarding the transfer of training effects between compensatory exploration and reading training, research suggests that these interventions are task-specific. Exploration training improves search abilities without enhancing reading, while reading training enhances reading performance without impacting exploration (Lane et al., 2010; Schuett et al., 2012; Zihl et al., 2021; Postuma et al., 2024). This lack of transfer likely arises from their distinct oculomotor demands—reading depends on small, precise horizontal saccades, whereas exploration requires large, multidirectional saccades (Aimola et al., 2014; Schuett et al., 2012).

In summary, the most effective rehabilitation for HVFDs requires a multifaceted approach, with compensatory strategies currently showing the most promise. Traditionally conducted on a PC screen, compensatory scanning training has strong empirical support, but the use of virtual reality (VR) may

enhance its effectiveness by offering a more immersive experience and enabling training across a larger portion of the visual field.

While VR has been explored in audiovisual, cognitive, and restitutive therapies for HVFDs (Daibert-Nido et al., 2021; Tchao et al., 2024; Dehn et al., 2020; Namgung et al., 2024), its application in compensatory training remains largely unexplored. Initial studies have demonstrated the feasibility and usability of VR-based compensatory training for individuals with HVFDs. For example, Gestefeld et al. (2020) reported that patients had a largely positive experience using a head-mounted VR display during visual rehabilitation training. Similarly, Knobel et al. (2021) developed an immersive visual search task tested in both healthy adults and patients with hemispatial neglect, with participants rating it as engaging and motivating. However, current evidence is limited to small sample sizes, with little data on the efficacy of VR in improving functional outcomes. Given VR's potential to boost engagement, improve adherence, facilitate the exploration of a larger portion of the visual field, and enable independent home-based training, further research is essential to assess its effectiveness in compensatory rehabilitation.

### ***Study objectives***

Initial findings suggest that VR-based compensatory training is both feasible and well-received, but, to our knowledge, no studies have tested its impact on visual exploration and reading outcomes. The present study aims to address this gap by evaluating the feasibility and efficacy of a home-based VR visual search training program for patients with HVFDs.

Specifically, we replace the standard computer monitor with a head-mounted display (HMD), creating a more immersive visual experience. This setup allows for a significantly larger visual field to be stimulated and enables the use of head-movement sensors in the HMDs to adjust visual content based on the participant's head orientation. However, this head-tracking input can also be disabled, allowing us to implement two distinct training formats. In the first format, head-movement sensors are turned off, meaning the visual display remains fixed regardless of head movements. This approach focuses solely on eye movements and is referred to as eye movement training (EMT). In the second format, head-movement sensors are activated, allowing participants to reveal new parts of the virtual environment by turning their heads—moving left exposes additional visual information on the left, and the same applies to rightward movements. This creates the impression of a stable, expansive virtual world that can be actively explored through head movements, a method we call head-movement training (HMT). HMT allows participants to explore a broader virtual space filled with visual stimuli, but doing so requires coordinated head movements. This training is designed to encourage

not only eye movements but also head movements and their combined use, offering a more dynamic and integrative visual exploration experience.

It was the aim of our study to examine the impact of different training conditions on oculomotor behavior and performance in visual search and reading tasks. We designed a study in which participants progressed through three distinct training phases, each lasting four weeks, with outcome measurements conducted before training, between phases, and after the final phase. The first training phase served as a placebo condition, where stimuli were presented only on that hemifield of the screen that projects onto the unaffected, healthy visual field. In the second phase, participants underwent EMT, during which stimuli were presented on both hemifields of the screen. However, neither eye movements nor head movements changed what is presented onto the HMD. The content on the HMD remained stationary. In this respect, the EMT condition resembled most closely the typical presentation modus used for compensatory training on a PC. The third phase introduced HMT. Participants had to explore a larger virtual space, they were, thus, encouraged to use head movements in addition to eye movements.

### ***Hypotheses and research questions***

For visual search outcomes, we formulated several hypotheses and research questions. First, we hypothesize that the EMT phase will result in significant improvements in both performance and oculomotor outcomes compared to the placebo training, which we do not expect to influence these outcomes. Second, we aim to explore whether the additional training provided in the HMT phase will further enhance oculomotor behavior and visual search performance, building on the gains observed during the EMT phase. Lastly, considering the cumulative effect of training duration, we assume that overall performance after the two training phases (EMT and HMT) will be superior to performance following placebo training alone.

Exploration training primarily influences exploration performance. Therefore, we assessed its effectiveness using performance and oculomotor outcomes in visual search tasks as our main evaluation metrics. While we also examined reading performance, these measures proved more challenging to assess consistently. As a result, they were used only to provide supplementary insights into the outcomes of our training conditions and analyzed exploratively.

Another exploratory analysis examined whether HMT effectively increased head movements throughout the training. Since this phase is designed to encourage head movements as a compensatory strategy, we expect to observe a progressive increase in head movement engagement throughout the training period. By addressing these research questions, this study aims to evaluate

the feasibility and efficacy of VR-based compensatory training for HVFDs, contributing to the development of innovative rehabilitation approaches that ultimately have the potential to enhance patients' quality of life.

## **Methods**

### ***Sample***

Participants for this study were recruited from the neuropsychological outpatient clinic at the University of Munich, as well as from surrounding neurorehabilitation clinics and neurology or ophthalmology practices. Eligible patients had to present with HVFDs, specifically hemianopia or quadrantanopia. In response to recruitment challenges during the COVID-19 pandemic, the criteria were further relaxed to include spatial neglect as a comorbidity, in addition to visual field defects. Participants were required to be at least 3 months post-stroke or post other neurological injury to reduce the impact of spontaneous recovery. Originally, we planned to recruit patients 6 months after neurological injury, but due to the recruiting constraints imposed by the COVID-19 pandemic, the inclusion period was adjusted to 3 months.

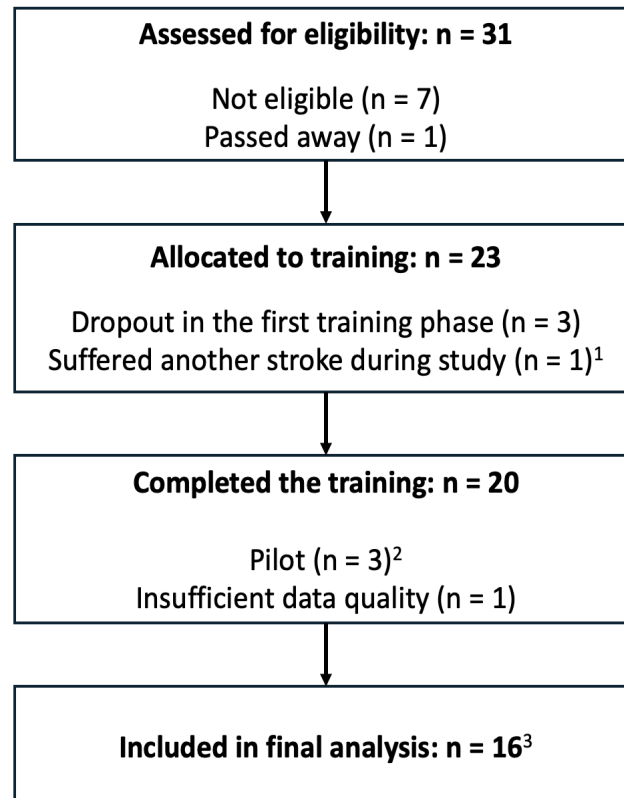
Additional inclusion criteria ensured participants could understand instructions and were capable of providing informed consent. This was verified through a neuropsychological assessment of memory and attention, ensuring that participants were able to comprehend and follow training and test instructions, as well as retain and recall these instructions for independent training at home. Participants were excluded if they had acute psychiatric disorders. Further eligibility requirements included intact or corrected visual acuity (e.g., with glasses or contact lenses) and the absence of eye diseases that would significantly impair vision or hinder the ability to see training stimuli and read instructions. Additionally, participants had to have no motor impairments in their dominant arm or hand to ensure they could independently operate the VR controller. Participants provided written informed consent after being fully informed about the study's purpose, procedures, and potential risks. The study was approved by the Ethics Committee of Faculty 11 for Psychology and Educational Sciences at the University of Munich.

A total of 31 patients were assessed for eligibility, with 8 deemed ineligible (including 1 who passed away). The remaining 23 patients were allocated to training; however, 3 dropped out during the first phase—2 due to the training being too difficult and 1 for personal reasons. One patient experienced another stroke during the study but resumed and completed the training a year later. This left 20 patients who completed the training. Three pilot patients, who had different training settings, study

design (without placebo training), and technical issues, were excluded from the analysis, along with 1 patient due to insufficient data quality. As a result, 16 patients were included in the final analysis, though not all had data at every time point (refer to the *Data Analysis* section for further details). A flowchart is provided in *Figure 1*.

**Figure 1**

*Flowchart of Participant Selection and Analysis*



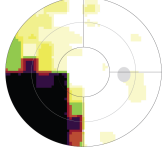
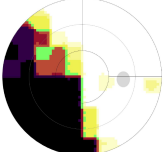
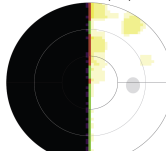
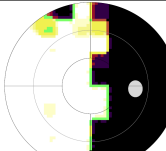
*Note.* <sup>1</sup> Patient experienced another stroke during the study but resumed and completed the training a year later. <sup>2</sup> Pilot patients were excluded from the analysis. <sup>3</sup> Not all 16 patients were included in each analysis.

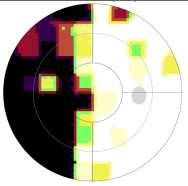
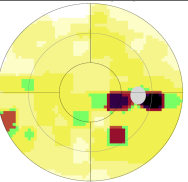
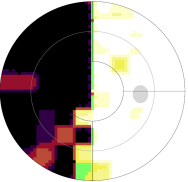
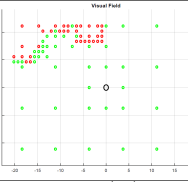
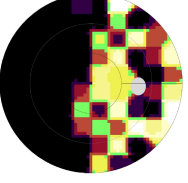
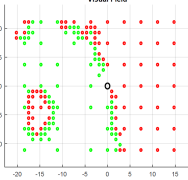
The final sample consisted of 16 patients (11 male, 5 female). Six patients ("bs," "cx," "fe," "jm," "lo," "tl") were diagnosed with left hemianopia, while three patients ("ew," "mr," and "xi") had right hemianopia. Two patients exhibited left lower quadrantanopia ("ac" and "sc") and two presented left upper quadrantanopia ("kx," "zj"). Additionally, two patients ("ev" and "zg") had right lower quadrantanopia. One patient ("hp") had a right-sided homonymous visual deficit in the form of right-sided paracentral scotomas. Patients varied considerably in age (range = 36–85 years,  $M = 56.75$ ,  $SD = 15.71$ ) and time since lesion onset (TSO), which spanned from 3 to 435 months ( $M = 43.5$ ,  $SD = 105.21$ ), reflecting different stages of recovery. The etiology of brain damage was highly heterogeneous, including ischemic and hemorrhagic strokes, traumatic brain injuries, progressive neurological

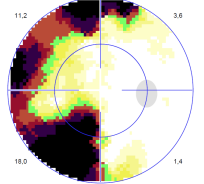
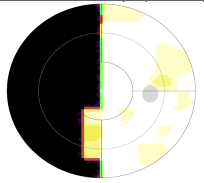
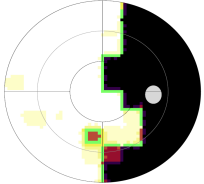
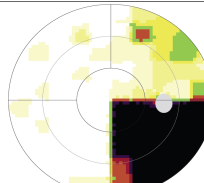
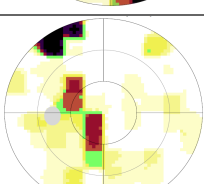
diseases, and brain tumors. Additionally, several patients had notable comorbidities, including left spatial neglect ( $n=4$ ), epilepsy ( $n = 4$ ), cognitive impairments ( $n = 3$ ), and motor deficits ( $n = 4$ ), further highlighting the diversity of the sample. Patient "ac" was included despite having progressive vasculitis, as this condition increases the risk of new lesions over time but does not necessarily indicate continuous deterioration. Notably, "ac" experienced no new events prior to or during the study period. Overall, this sample represents a diverse clinical population with considerable variability in lesion chronicity and neurological impairments (see *Table 1* for more details).

**Table 1**

*Demographic and clinical information of the patient sample*

<b>Patient</b>	<b>Gender</b>	<b>Age</b>	<b>TSO (months)</b>	<b>Etiology</b>	<b>Visual field disorder</b>	<b>Comorbidities</b>	<b>Perimetry</b>
<b>ac</b>	male	44	36	Primary progressive CNS-vasculitis	Left lower quadrantanopia	Symptomatic epilepsy (medically treated)	
<b>bs</b>	male	54	43	Right hemisphere ischemia due to dissection of the right internal carotid artery	Left hemianopia	Left neglect, left hemiplegia	
<b>cx</b>	male	51	17	Malignant melanoma, metastasized, not surgically targeted	Left hemianopia	Left hemiparesis	
<b>ev</b>	female	51	12	Subarachnoid haemorrhage with ruptured aneurysm of left anterior communicans artery; Partial infarction of the left parieto-occipital middle cerebral artery	Right lower quadrantanopia	Reading impairment (can read single words but cannot read or understand longer texts), memory impairment, mild cognitive disorder	Custom lab perimetry was completed, but results were unusable due to poor fixation and many missed stimuli
<b>ew</b>	male	56	25	Right medial infarction, left posterior infarction	Right hemianopia	None	

<b>fe</b>	female	74	5	Subacute right middle cerebral artery infarction, with two microischemic lesions in the bifrontal region (embolic stroke of undetermined source)	Left hemianopia	Left neglect, impaired fine motor skills of left hand, latent left arm paralysis, attention deficit disorder	
<b>hp</b>	male	70	6	Ischaemic stroke	Right-sided paracentral scotomas	None	
<b>jm</b>	male	76	5	Multiple embolic subacute infarctions in the right thalamus (basal-temporal) and in the right occipital lobe	Left hemianopia	Epilepsy (left frontal, first diagnosed 2011) with postictal amnesic syndrom, polyneuropathy, lens opacity after cataract surgery	
<b>kx</b>	male	37	3	Stroke in the coverage area of right cerebral posterior artery (embolic stroke of undetermined source)	Left upper quadrantanopia	None	
<b>lo</b>	male	63	37	Traumatic brain injury with right hemispheric intracerebral hemorrhage	Left hemianopia	Left neglect, epilepsy with generalized and focal seizures (medically treated), cataract of both eyes (surgically treated)	
<b>mr</b>	male	42	6	Metastases resection after malignant melanoma	Right hemianopia and incomplete left upper quadrantanopia	Memory impairments	

<b>sc</b>	male	78	17	Ischemia of the middle cerebral artery	Left lower quadrantanopia	Left neglect	
<b>tl</b>	female	50	435	Pilocytic astrocytoma, right parieto-occipital. Resection in 1983 and 1993	Left hemianopia	Epilepsy (resection of the residual epileptogenic focus, temporo-occipital) in 2003, no seizures since 2014 (medicated with Levetiracetam)	
<b>xi</b>	male	36	8	Multiple infarcts in the posterior circulation (etiology unclear - embolic)	Right hemianopia	Short-term memory impairment	
<b>zg</b>	female	41	30	Oligodendroglioma in the left parietal lobe (surgical intervention and chemotherapy)	Right lower quadrantanopia	Multiple sclerosis (diagnosed 2005); dyslexia and anomia after brain surgery (anomia almost resolved, reading still remains difficult)	
<b>zj</b>	female	85	11	Embolic ischemia in the right posterior cerebral artery, right hemispheric infarction due to acute cardioembolic occlusion of the internal carotid artery	Left upper quadrantanopia	Left arm hemiparesis	

*Note.* Age and gender were self-declared via a demographic questionnaire; TSO = time since lesion onset (calculated from the month of the lesion as stated in the medical report to the first month of study participation); Octopus perimetry of the dominant eye with 30° radius (for patient "sc," a different software version (EyeSuite V2.3.0 instead of 3.1.0) was used for perimetry, resulting in a slightly different output format). For cases without Octopus perimetry, visual field test results from custom lab perimetry are provided. Green circles = seen test points; red circles = missed test points.

### ***Study design and procedure***

Prior to participation in the VR-based visual exploration training, each patient underwent a comprehensive initial assessment to ensure eligibility and to tailor the intervention to their specific needs. This assessment included several domains, including anamnesis, neuropsychological testing, optometric examinations, and detailed evaluation of visual field deficits.

The assessment began with anamnesis, which involved collecting a thorough self-report from the patient, alongside a review of previous neurological and neuropsychological reports and assessments. This step was critical for understanding the patient's medical history, including any past or ongoing neurological conditions, and identifying potential factors that could influence the training outcomes. Patients were also asked to answer the questions of the Cerebral Vision Screening Questionnaire (CVSQ; Neumann et al., 2016), which provided insights into vision-related challenges commonly associated with neurological events such as hemianopic alexia and visual exploration deficits.

The neuropsychological assessment employed standardized and sensitive tools to delve deeper into cognitive and attentional functions. The auditory intrinsic alertness and visual selective attention subtests from the 'Perception and Attention Functions' (WAF) test battery of the Vienna Test System (Sturm, 2006) were administered to evaluate attentional capacities. To detect unilateral spatial neglect, patients completed subtests from the Neglect-Test (NET, Fels & Geissner, 1997), including line crossing, line bisection, star cancellation, figure copying, as well as the single task of the Sensitive Neglect Task (SNT; Reinhart et al., 2016). Tactile and acoustic extinction (i.e., failure to detect a contralesional stimulus when an ipsilesional one is presented simultaneously) tests were performed to further evaluate visuospatial attention without relying on visual stimuli. Memory assessments included the Logical Memory Test from the Wechsler Memory Scale-IV (Wechsler, 1945) and delayed recall of face recognition from the Rivermead Behavioural Memory Test (Wilson et al., 1989). Together, these tests provided a detailed profile of the patient's memory capabilities.

Finally, optometric evaluations ensured a thorough understanding of the patient's visual capabilities. The blind and sighted portions of the visual field were mapped using static Octopus 900 perimetry with 30° radius, assessing the current state of the visual field deficit and enabling the customization of training to address specific deficits. For patients with confirmed or potential eye diseases identified during anamnesis, further optometric tests were conducted, such as visual acuity measurement using refractive tests and retinal analysis via optical coherence tomography, encompassing optic nerve head scans, retinal nerve fiber layer thickness, ganglion cell layer thickness, and hemisphere asymmetry measurements. By integrating all the above-mentioned assessments, we gained a comprehensive

understanding of each patient's neurological, cognitive, and visual status while ensuring that only those meeting the study's inclusion criteria were enrolled.

Upon admission to the study, patients completed a pre-test assessment of outcome measures, which included evaluations of reading performance and visual exploration capabilities. These pre-tests served as baseline measurements for subsequent comparisons. Following the pre-tests, patients attended an initial training session where they received detailed instructions on how to use the VR device. This session included hands-on practice, during which the patients were guided until they demonstrated confidence in independently operating the device and initiating the training protocol.

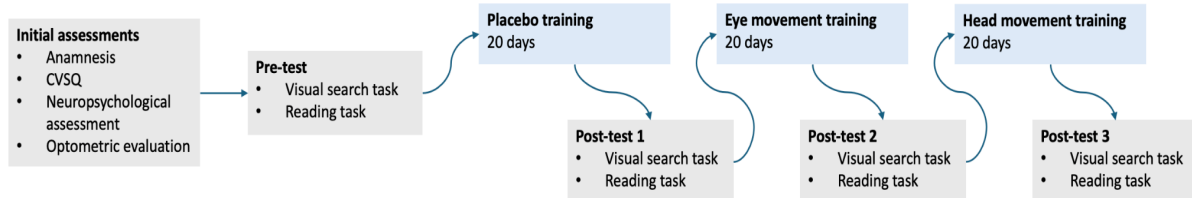
Patients then progressed through three distinct training phases, each lasting 20 days. During the placebo training phase, stimuli were presented exclusively on the side of the VR screen corresponding to the participant's intact visual field. This phase served as a control condition, allowing for comparison with the subsequent active training phases. During the eye movement training phase (EMT), stimuli were presented across all areas of the VR screen, but the VR environment was programmed to move in sync with the participant's head movements. This setup ensured that head movements did not alter the content displayed on the HMDs. In the final phase, head movement training (HMT), the screen remained stable during head movements while a broader visual space was filled with stimuli, prompting participants to explore the larger virtual environment using both head and eye movements. The fixed order of the active training phases, starting with eye movement training followed by head movement training, allowed participants to build foundational skills before progressing to more complex tasks. By mastering eye movements first, participants can focus on a simpler task, building confidence. This progression mirrors real-life visual exploration, where individuals use eye movements to focus on areas of interest before incorporating head movements to shift the visual field. Patients also had the opportunity to provide additional notes regarding technical difficulties, interruptions, or any other observations about the training sessions. After completing each training phase, patients underwent post-test evaluations identical to the pre-tests, during which behavioral and oculomotor parameters were assessed. See *Figure 2* for an overview of the study procedure.

Originally, the study was planned as a randomized, blinded, controlled trial, where the experimental group would first undergo EMT, followed by HMT, while the control group would receive placebo training before EMT and HMT. This design aimed to compare the effects of active training phases with placebo training, minimizing carryover effects. However, due to patient recruitment challenges during the COVID-19 pandemic, this larger sample-based design was not feasible. As a result, the study was adapted to a within-subject design, where each participant serves as their own control and completes all three training phases. This approach reduces the required sample size and avoids the challenge of

ensuring comparability between separate groups, which is particularly difficult in heterogeneous patient samples, as required in a between-subject design. However, it also makes carryover effects unavoidable.

**Figure 2**

*Overview of study participation steps for each patient*



### ***Pre- and post-tests***

#### *Apparatus*

Stimuli were generated using MATLAB R2015a (MathWorks, Natick, MA) and the Psychophysics Toolbox Version 3 (Brainard, 1997; Kleiner et al., 2007), and displayed on a 532x299 mm monitor with a 144 Hz refresh rate. Gaze position was recorded with a table-mounted Eyelink 1000 Plus system (SR Research, Mississauga, Ontario, Canada) at a sampling rate of 2000 Hz. To reduce head movements and enhance eye tracking accuracy, participants rested their head on a chin rest. The distance from the eye to the upper part of the screen was 705 mm, and 750 mm to the lower part. Calibration involved a 9-point procedure using black rings on a white (for the reading task) or grey (for the visual search task) background, repeated as needed to ensure accuracy. Successful calibration was defined by a deviation of no more than 1.5° visual angle for each point. The dominant eye was used for tracking, with a switch to the non-dominant eye if calibration quality was insufficient.

#### *Reading task*

Patients were given three texts to read consecutively. The first two texts were read silently, while the third was read aloud and recorded with an audio device. Patients were directed to read the texts displayed on the screen as fast and accurately as they could and to notify completion by pressing a button. The texts, displayed in Arial 24-point font on white background, were left-aligned with 1.5 line spacing and filled the entire screen. Following each text, the researcher posed two yes-or-no questions about the content to verify that the patients had actively read the material rather than merely glancing at it. The reading task featured four versions corresponding to four measurement time points, each containing three unique texts, with a total of 12 texts. These versions were randomly assigned across patients and time points, ensuring each patient encountered each version once.

Four texts from the Saarbrücker Lesetest (SBL; Kerkhoff, Wimbauer & Reinhart, 2015) were chosen for loud reading due to their narrative style and limited familiarity (see *Figure 3*). These texts, derived from *Die Schildbürger* by Karl Simrock (16th century), each contain approximately 180 words. Since the SBL lacked enough texts for four reading task versions with three texts each, additional texts were taken from the International Reading Speed Test (IReST; Hahn et al., 2006; Trauzettel-Klosinski et al., 2012). The IReST includes standardized expository texts (132 words each,  $\pm 3.2$ ) in 17 languages, aimed at 9–12-year-old lexical abilities, with low-frequency words excluded and syntax designed per Gibson's (2000) syntactic prediction locality theory. Both SBL and IReST texts were constructed to measure reading speed and errors but differ in style, word frequency, and syntax—SBL texts are narrative, while IReST texts are neutral and factual. Notably, SBL construction did not control for word frequency or syntax.

We conducted a study with 15 healthy native German speakers (9 female, 6 male;  $M_{age} = 28.8$ ,  $SD = 13.57$ ) to compare these two tests. Participants read six texts from each reading test (three aloud, three silently), with behavioral and oculomotor parameters assessed. Results showed significantly lower words per minute (wpm), a metric that combines both reading speed and accuracy, for SBL texts ( $M = 159.24$ ,  $SD = 25.64$ ) compared to IReST texts ( $M = 169.36$ ,  $SD = 21.42$ ;  $z = -3.38$ ,  $p = .001$ ,  $r = .94$ ), see *Figure 4*. Differences in reading aloud duration ( $z = -3.38$ ,  $p = .001$ ,  $r = .94$ ) and number of errors ( $z = -2.14$ ,  $p = .033$ ,  $r = .59$ ) were also significant. No significant differences were found in oculomotor parameters or silent reading duration. The lower wpm in SBL texts likely stems from outdated, low-frequency words (e.g., "Waschkörbe," "andre") originating from 16th-century sources. Given their limited comparability, it is appropriate to use texts from these two tests for different reading modalities, as we did in our study—SBL for loud reading and IReST for silent reading.

**Figure 3**

*Example text from the Saabrücker Lesetest*

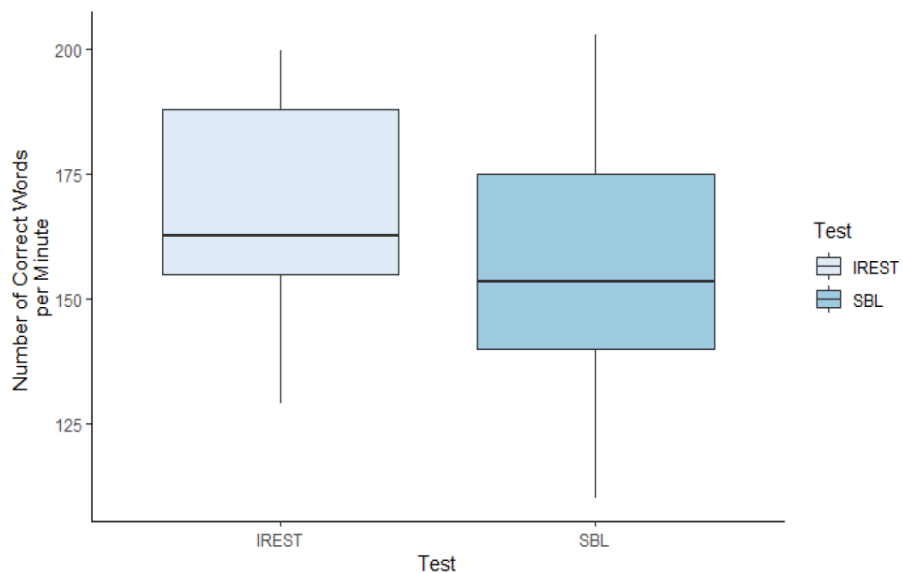
Eines schönen Tages wurde in Schilda das Salz knapp. Und die Händler, die durchs Land zogen, hatten keines zu verkaufen. In Salzburg sei Krieg, erzählten sie. Und in Salzbrunn und in Salzwedel auch. Und man müsse warten, bis der Krieg vorüber sei. Das missfiel den Schildbürgern. Denn Butterbrot ohne Salz, Kartoffeln ohne Salz und Suppen ohne Salz schmeckten ihnen und ihren Kindern ganz und gar nicht. Deshalb beratschlagten sie, was geschehen solle. Und weil ihr Rathaus nun helle Fenster hatte, fiel ihnen auch gleich etwas Pfiffiges ein.

Da der Zucker auf Feldern wachse, meinte einer, sei es wohl mit dem Salz nicht anders. Man brauche deshalb auf dem Gemeindeacker, der noch brach liege, nur Salz auszusäen, alles andere werde sich dann schon finden.

So geschah's. Sie streuten die Hälfte ihres Salzvorrats auf den Acker, stellten Wachtposten mit langen Blasrohren an den Rändern des Feldes auf, für den Fall, dass die Vögel das Salz würden stehlen wollen, und warteten ab. Schon nach ein paar Wochen grünte der Acker, dass es eine Lust war. Das Salzkraut schoss nur so in die Höhe.

**Figure 4**

*Comparison of Words per Minute for IReST and SBL*



### *Visual search task*

Visual exploration was assessed through a visual search task, where patients were required to identify a slightly tilted line (target) among vertical lines (distractors), as shown in *Figure 5*. They indicated target presence by pressing the first button on the button box and target absence by pressing the second. The target appeared in half of the trials, with target-present and target-absent trials presented in random order. The task consisted of 96 trials, plus 10 practice trials, which were repeated if accuracy fell below 60%. Patients received feedback on accuracy only after the practice trials; no feedback was provided thereafter.

Each trial included 16 stimuli, all black and measuring  $0.5^\circ$  in size, displayed on a grey background. Stimulus positions were determined by a grid system with three eccentricity levels and four quadrants, with distractors randomly distributed across these dimensions. The target could appear with equal probability at all eccentricity levels and quadrants. For each trial a new, random target position was selected. Trials began with an 800 ms fixation period, using the fixation target shape recommended by Thaler et al. (2013) for calibration. The fixation target was  $1^\circ$  in diameter. If the gaze position deviated beyond a  $2^\circ \times 2^\circ$  window around the fixation target, the calibration procedure was repeated. Patients were instructed to begin each trial by focusing on the screen center, where the fixation target appeared. There was no limit on stimulus presentation time. After responding, the display disappeared, followed by a 1000 ms blank screen (inter-trial period).

### **Figure 5**

*Example trial from the Visual Search Task*



*Note.* Target-present trial in the visual search task. The target was a tilted line, while the distractors were straight lines.

## **Training**

### *Hardware and software*

For the training, two VR applications were developed using Unity: one for Google Daydream and another for Oculus Go. These applications were distributed as Android Package (.apk) files and installed on their respective devices.

The Google Daydream application was installed on a Motorola Z smartphone, which met the hardware and software requirements for Daydream compatibility (Android Nougat 7.1 or later). The smartphone was inserted into the Daydream View headset, a lightweight, fabric-covered VR headset equipped with adjustable straps for secure placement and a handheld controller with a touchpad and buttons for intuitive interaction (see *Figure 6*).

Although the Daydream system provided an affordable and accessible platform for VR training, several limitations were encountered during pilot testing. Patients reported directional drifting of the VR environment during head movement training, which led to misaligned visual stimuli as sessions progressed. Additionally, the limited compatibility of the Daydream platform and the lack of robust technical support following its discontinuation in 2019 posed challenges for its use in clinical settings. Consequently, the study transitioned to using the Oculus Go headset for head movement training to ensure more reliable performance.

### **Figure 6**

*Daydream view headset, controller and the compatible Motorola Z smartphone used in the study*



The Oculus Go application was installed directly on the standalone Oculus Go headset, which does not require a PC or smartphone to operate. The device features a 5.5-inch fast-switching LCD with a resolution of 1280 × 1440 pixels per eye and a refresh rate of 60–72 Hz. Like the Daydream View, the Oculus Go employs 3-degrees-of-freedom tracking for rotational movements and includes a controller for interaction within the virtual environment.

The Oculus Go offered several advantages for the study, including its wireless and portable design, lightweight construction with breathable facial padding, and user-friendly setup. Notably, no drifting issues were reported during training sessions, addressing a critical limitation observed with the Daydream system. Despite its advantages, the Oculus Go's relatively short battery life required frequent recharging during extended sessions. Support and software updates ceased following its discontinuation in 2020, but this did not impact its functionality during the study period.

### *Training process*

The VR exploration training program consisted of a series of search tasks designed to enhance visual exploration. Each training set comprised 50 consecutive trials, where patients were tasked with determining as quickly and accurately as possible whether a target stimulus was present among distractors.

Upon launching the application, patients were greeted and prompted to confirm their identity by performing three clicks. After verification, instructions were provided according to the selected training type. For placebo and eye movement training, patients were instructed to move their eyes while keeping their head and body still. For head movement training, they were instructed to move both their eyes and head while refraining from moving their body. Following the instructions, the application presented the parameters of the current training session. Patients were encouraged to review these details and familiarize themselves with the target and distractor stimuli. Once prepared, they could proceed to the search task by clicking to advance to the next screen. A search image was then generated. The search task difficulty increased across the 40 levels of the training program, with systematic adjustments in the following parameters:

- Target eccentricity: The distance of the target stimulus from the center of the display increased progressively across levels.
- Stimulus count and complexity: Number of stimuli increased from 8 in the first level to 50 in the last level and ranged from simple shapes to letters and complex figures.

- Blind-side presentation probability: For patients with hemianopia, the likelihood of target presentation on the "blind" side increased from 40% in early levels to 80% in later levels. For quadrantanopia, the probability of the target being presented in the affected quadrant ranged from 20% to 40%. This doesn't apply to placebo training, where all stimuli were presented on the side of the screen corresponding to the sighted side of the visual field. Refer to *Appendix, Table 1* for an example of training settings across all levels.

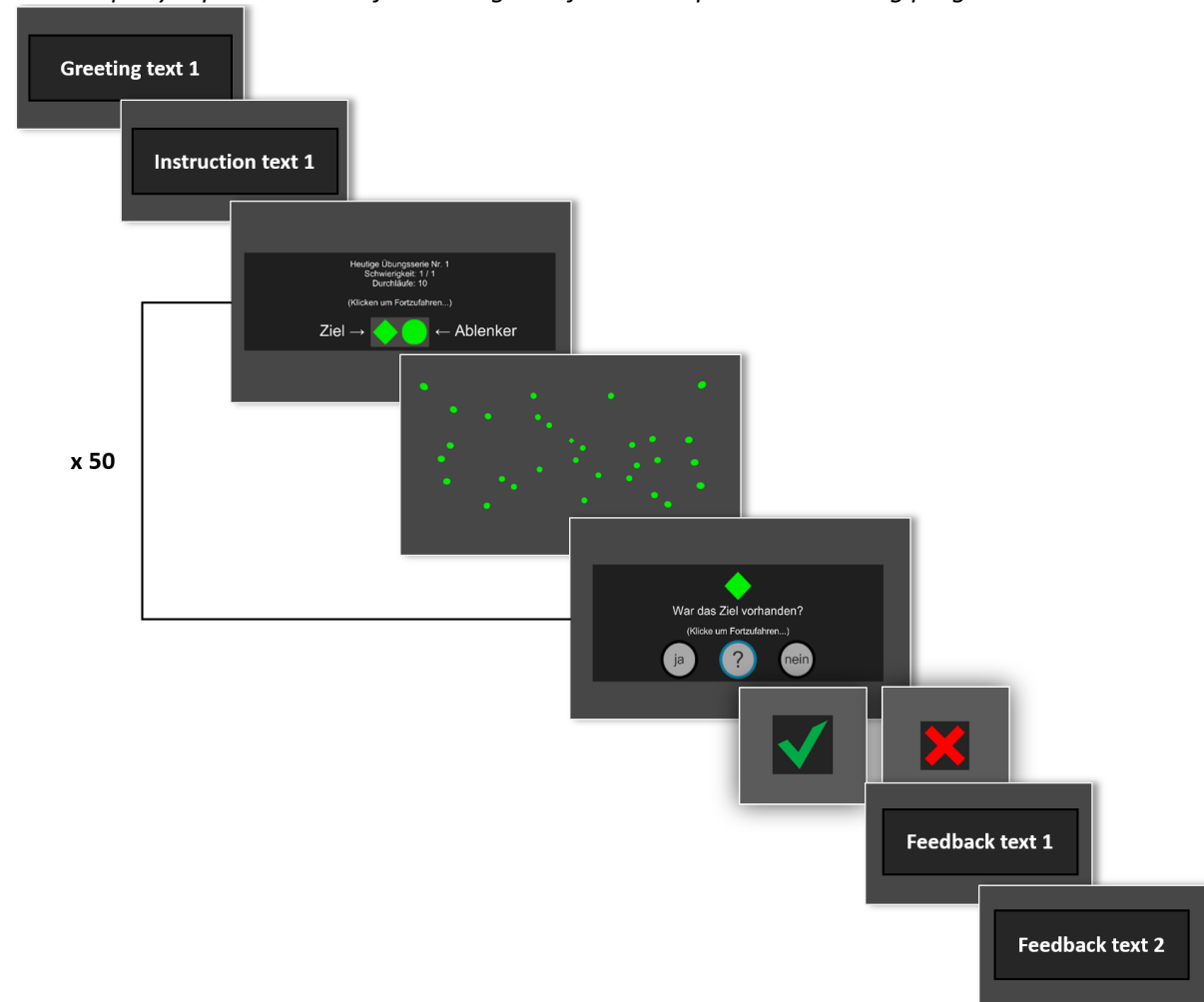
During the first training set of each level, the search image remained visible without a time limit, allowing patients to complete the task at their own pace. Search times—measured from the onset of the search image to the click indicating the end of the search—were recorded and stored. In subsequent training sets at the same level, the presentation time of the search image was adjusted based on the patient's performance, limited to the 80th percentile of their search time distribution from the initial training set. This adaptive timing ensured that each level was practiced at least twice: once with unlimited time and once under time constraints. Progression to the next level depended on performance during time-limited trials.

After each search trial, patients were required to indicate whether the target was present ("Yes" or "No") and confirm their selection with an additional click to minimize errors. To prevent accidental responses, user input via the controller was disabled for the first 500 milliseconds of each trial, establishing the minimum reaction time. Immediate feedback was provided after each trial, displaying whether the response was correct. Patients had to click to proceed to the next trial.

Upon completing all 50 trials, a summary of the session's results, including accuracy rate and average response time, was presented to the patient. Patients clicked to proceed, after which the data were saved. If the application was not terminated, the difficulty level for the next training set was adjusted based on the accuracy rate. A success rate of 94% or higher resulted in progression to the next level. A success rate of 80% or lower led to a downgrade to a lower level. If the success rate fell between 80% and 94%, the current level was repeated. An exemplary illustration of the training process can be found in *Figure 7*.

**Figure 7**

*An exemplary representation of a training set of the VR exploration training program*



*Note.* Screenshots of the training process (top to bottom): (a) greeting screen and identity confirmation, (b) training instructions, (c) introduction of target and distractor stimuli, (d) search image, (e) answer selection screen, (f) feedback after each trial, (g) summary feedback after 50 trials, and (h) data-saving screen with options to continue or end the session. Instructions and text were presented in German.

### *Training stimuli*

The stimuli for the VR training program were created using Microsoft PowerPoint and saved as .png files. For enhanced graphical representation, some images were converted to TGA format using the GNU Image Manipulation Program (GIMP 2).

Stimulus count and complexity increased across the 40 training levels to match the intended difficulty gradient. Each training level featured two possible stimulus pairs (target-distractor combinations) that were selected randomly. To avoid repetitive learning with the same stimuli, these pairs were repeated for two consecutive levels before being replaced by a new set of pairs (e.g., Levels 1 and 2 used one







set of pairs, while Levels 3 and 4 used another). The type and complexity of stimuli varied progressively across the levels (see *Figure 8* for a visual example). Levels 1 to 12 featured simple geometric shapes, such as a red triangle as the target and a red square as the distractor. Levels 13 to 28 used letters, with the target being the original letter and the distractor being a mirrored or flipped version (e.g., an "L" and a mirrored "L"). Levels 29 to 40 involved complex shapes with subtle differences, such as a Landolt C as the target and the same stimulus rotated by 90° as the distractor.

Stimuli were displayed in a VR environment developed using Unity. They were distributed across a spherical surface, with the patient's viewpoint positioned at the sphere's center, ensuring that all stimuli were equidistant from the user. The radius of the sphere was set to 2.1 Unity units. Stimuli were randomly arranged on a near-uniform grid on the spherical surface. The grid spacing was 0.005 Unity units, and the stimulus size was 0.02 Unity units. The area of stimulus presentation varied depending on the training type. For placebo and eye movement training, stimuli were restricted to a maximum longitude and latitude of 27° on the spherical surface. In contrast, for head movement training, stimuli extended to a maximum longitude of 90° and latitude of 30°.

The distance of the target stimulus from the center of the display (i.e. target eccentricity) increased progressively across levels. The maximum target distance from the screen's center was determined by linear interpolation between a minimum deviation value (0.2) and a maximum deviation value (1.0), based on the current difficulty level. Within this range, the actual target distance for each question was randomly assigned to a value between 0 and the interpolated maximum distance. All stimuli were presented against a dark gray background. Instructional text and all other text elements were white and displayed on a semi-transparent black background for optimal readability.

**Figure 8**

*Examples of training stimuli across levels*

Levels	Target	Distractor
1-12		
13-28		
29-40		

*Note.* Levels 1–12 featured simple shapes with easily detectable differences. Levels 13–28 used letters, with the target being a mirrored or upside-down version of the original. Levels 29–40 included complex shapes with more subtle differences.

## Data Analysis

Data preprocessing, including the extraction of fixation behavior data, was performed using Matlab (Version R2016a). For data processing of HMT data, as well as descriptive and inferential statistical analysis, R (Version 4.2.0; 2022-04-22) was utilized. Given the within-subject design of the study, statistical analyses primarily employed paired-sample t-tests. When assumptions for parametric testing were violated, non-parametric alternatives, such as the Wilcoxon test, were applied. Specifically, non-parametric tests were used when the Shapiro-Wilk test for normality indicated significant deviations from normal distribution and when Levene's test suggested a lack of homogeneity of variances. Outliers were identified and excluded using the interquartile range (IQR) method. Results are presented both with and without outliers. For effect size estimation, Cohen's  $d$  was calculated for t-tests, and for the Wilcoxon tests, the effect size estimate  $r$  was derived by transforming the p-value into a z-value and applying the formula:  $r = z/\sqrt{N}$ , where  $N$  represents the total sample size (Field et al., 2012, p. 665).

Improved visual search performance is characterized by faster search times, accompanied by fewer saccades and larger saccadic amplitudes. Additionally, post-training improvement is associated with increased and larger eye movements into the blind field. In this study, search time served as the primary outcome measure, while all oculomotor variables were considered secondary outcome measures. Specifically, we analyzed the following variables:

### *Primary Outcome Measure:*

- Search time: The mean search time in correct, target-present trials, measuring how quickly participants locate a target. If a significant difference in search time was found, search accuracy was also examined to assess potential speed-accuracy trade-offs. Accuracy was defined as the percentage of correct responses, i.e. the correct identification of both target-present and target-absent trials.

### *Secondary Outcome Measures (Oculomotor Variables):*

- Number of saccades and saccadic amplitude: The mean number and amplitude of saccades in correct, target-present trials, aligning with the search time analysis since both variables influence search time.
- Percentage of saccades toward the blind field: The percentage of first saccades directed into the blind field in correct, target-present trials, only for trials in which the target was placed in the blind field. This specific subset was chosen to eliminate the potential confounding factor of incorrect

responses, as well as to focus on trials in which exploring the blind field first would actually provide an advantage. If the target was in the sighted field, there would be no real benefit to initially directing gaze toward the blind field.

- Saccadic asymmetry: The mean asymmetry of saccadic amplitude in target-absent trials, reflecting differences in saccadic amplitude between the blind and sighted fields. Target-absent trials were used to isolate inherent saccadic behavior without the influence of target presence.

Three planned comparisons were conducted to test the main hypotheses related to visual search outcomes:

1. Placebo vs. EMT: To assess the isolated effects of placebo training compared to EMT, differences were computed between pre-training and post-placebo measures, as well as between post-placebo and post-EMT measures. Absolute differences were then compared using one-sided paired-sample t-tests (or their non-parametric equivalent), with the hypothesis that EMT would improve visual search outcomes more than placebo training, which was expected to have no effect.
2. EMT vs. HMT: To compare the efficacy of EMT versus HMT, we first calculated the specific benefit of each training. For EMT, the benefit was determined by the change in performance resulting from its introduction (i.e., performance (EMT) – performance (placebo)). For HMT, the reference point was the performance following EMT, as HMT was always conducted after EMT. Therefore, the HMT benefit was defined as performance (HMT) – performance (EMT). We then used two-sided paired sample t-tests (or their non-parametric equivalent) to compare the benefits of EMT and HMT.
3. Cumulative effects of EMT and HMT: To evaluate the combined effects of both training phases, performance after HMT was compared to performance after placebo training (with EMT preceding HMT). A one-sided paired-sample t-test (or its non-parametric equivalent) was used for this comparison, with the hypothesis that the two training phases together would yield a positive effect on visual search performance compared to placebo training.

Due to incomplete participation and insufficient data quality, not all participants were included in every comparison. For the first analysis, the sample size (N) was 16. For the second and third analyses, N was reduced to 11, as four patients did not complete the HMT phase, and one participant, "jm," had insufficient data at the post-HMT measurement.

## ***Exploratory analyses***

### *Reading*

Reading outcomes were assessed for both loud and silent reading tasks. For loud reading, we measured words per minute (wpm), which was calculated using the formula:  $wpm = ((\text{number of words per text} - \text{number of reading errors}) / \text{reading duration in seconds}) \times 60$ . For silent reading, oculomotor parameters were evaluated. In patients with right-sided HVFDs, we focused on the saccadic amplitude of rightward saccades, which is typically reduced in such cases. For patients with left-sided HVFDs, we examined the number of additional corrective saccades made during the return-sweep (the eye movement from the end of one line of text to the start of the next), an eye movement commonly impaired in left-sided HVFDs.

To ensure that only text-related eye movements were analyzed, eye movements were plotted relative to the text for each participant at each time point. Saccades occurring prior to the first line of text or after the last word was fixated for the first time were excluded. Due to a small sample size, reading outcomes were analyzed descriptively and exploratively. Several factors contributed to the reduced sample: some participants skipped the reading task due to fatigue, one was not a native German speaker and lacked a test version in his native language, and others had poor quality audio recordings, making the analysis of reading performance challenging. Additionally, separate parameters were considered for right- and left-sided HVFDs in silent reading, which further reduced the available data for analysis.

### *Head movements during HMT*

Head movement data were collected using an Oculus Go VR headset, which integrates sensors for rotational tracking, including a gyroscope, accelerometer, and magnetometer. These sensors allowed for measurement of head rotation along three axes: the X-axis (with positive values corresponding to forward tilt), the Y-axis (positive values corresponding to rightward movement), and the Z-axis (positive values corresponding to head tilt to the left). The tracking system sampled head rotations at a frequency of 60 Hz. For the analysis of head movements, only rotational movements in the horizontal plane (Y-axis) were considered.

To extract relevant head movements for analysis, we employed a segmentation approach based on previous research (Einhaeuser et al., 2007; Hamel et al., 2012; Tichener et al., 2019). Two thresholds were established to define horizontal head movements: (1) a velocity greater than  $6^\circ/s$  and (2) an amplitude threshold, or  $\Delta_{\text{head}}$ , defined as the difference between the rightmost and leftmost excursions of the head, which should be at least  $3^\circ$ . For each identified head movement, three key

metrics were quantified: the direction (left or right), the duration (in seconds), and the amplitude (in degrees). Head movements were shown to last between 200 and 800 ms in prior research (Fang et al., 2015). Consequently, movements shorter than 200 ms were excluded from the analysis to avoid capturing irrelevant data. An upper limit of 3 seconds was set for movement duration, as longer head movements are plausible in complex visual search tasks, especially in neurological patients.

To validate the segmentation approach, the average number of head movements was compared between target-present and target-absent training trials using a one-sided paired-sample t-test. Similar to eye movements, we hypothesized that more head movements would occur in target-absent trials.

To assess whether the training design led to an increase in head movements, we first approximated training progression by performing a quantile split on patients' horizontal target eccentricity distribution. This allowed us to classify trials into those with low and high target eccentricity, reflecting the increase in target eccentricity range as patients advanced through training levels. We then tested the hypothesis that search trials with high eccentricity would elicit more head movements than those with low eccentricity, using a one-sided paired samples t-test. Additionally, a similar analysis was conducted on trials with targets presented on the side of the visual deficit to examine whether head movements towards the blind side increased throughout the training, relative to those towards the sighted side.

Since head movements were only analyzed using the horizontal component, for patients with quadrantanopia, the entire side of the affected quadrant was considered the "blind" side. (e.g., in cases of left upper quadrantanopia, the left side was treated as the "blind" side, similar to a left hemianopia). It is important to note that the number of training sessions varied across patients. Some patients completed more sessions per day, while others were slower and completed less sessions, thus resulting in different numbers of sessions analyzed for each individual (range: 47 – 180). The final sample size for head movement analysis consisted of 13 patients. One participant, "oc", was excluded from the main analysis due to not receiving the placebo training, though they were included in the analysis for head movement data as they completed the head movement training.

## **Results**

### ***Neuropsychological assessments***

As part of the initial assessment, patients completed the Cerebral Visual Screening Questionnaire (CVSQ), with answers to selected relevant questions reported in *Table 2*. The first relevant item

assessed subjective awareness of visual changes since the onset of the condition. The majority of patients reported noticing visual deficits, while two participants (“hp” and “sc”) were unaware of any impairments and only became aware through medical evaluation. Reading difficulties in patients with visual field defects were addressed in the third question of the questionnaire. Nine patients reported experiencing reading problems. The fourth question focused on visual exploration deficits, specifically difficulties in avoiding obstacles or people. Ten out of fifteen patients reported such difficulties. Notably, one participant (“hp”) who initially denied subjective visual deficits responded affirmatively to this question. One patient (“bs”) did not complete the CVSQ and was excluded from this analysis.

Results of further neuropsychological assessments are presented in Table 3. The assessments revealed substantial variability in neglect, attention, and memory performance across patients. In the NET, most patients performed well on line and star cancellation tests (scores near 10), while others (“bs”, “sc”) exhibited marked deficits. Notably, “bs” showed particularly poor performance on line bisection and figure copying. The SNT indicated minimal spatial bias for most patients, with Center of Cancellation (CoC) scores near zero, though “zj” and “xi” demonstrated stronger leftward biases. Extinction testing identified acoustic extinction in four patients (“bs”, “cx”, “lo”, “sc”). Memory performance varied widely, with Logical Memory immediate recall scores ranging from 4 (“xi”) to 13 (“lo”) on a scale from 1 to 19. Recognition scores were generally within the 51–75th percentile, except for “xi” and “tl”, who scored significantly lower. RBMT results showed intact face recognition for most, except for “bs”, “fe”, “lo”, “mr”, “tl”, and “zj”. Attentional testing (WAF) showed that intrinsic alertness varied widely, with patients “ev”, “fe”, and “tl” scoring well above average, while “bs”, “sc” and “zj” exhibited way below-average performance. Unimodal selective attention was also highly variable, with some (“cx”, “zg”) scoring in the upper percentiles, whereas “bs”, “ev”, “fe” and “zj” performed rather poorly. Overall, results suggest a potential dichotomy between a group with relatively intact cognitive functions (e.g., “cx”, “ew”) and another exhibiting widespread impairments (e.g., “bs”, “xi”).

A comparison between neglect diagnoses in medical records and neuropsychological test performance revealed some discrepancies. Patients “bs”, “fe”, “lo” and “sc” were all diagnosed with left neglect based on medical records. However, their test performances varied. Patient “bs” showed widespread deficits across all NET subtests except for line cancellation and also exhibited acoustic extinction, confirming the presence of severe neglect. Patient “fe” displayed a different pattern, with impaired line bisection performance and a slight leftward shift in the CoC but no extinction, suggesting a milder neglect profile. Patient “lo” showed impaired performance on figure copying in the NET, a slight rightward CoC shift, and acoustic extinction, indicating some neglect-related impairments. Patient “sc” performed rather poorly on line bisection and star cancellation and had a slight rightward

CoC shift, alongside acoustic extinction, suggesting visuospatial deficits consistent with neglect. These findings highlight the complexity of assessing neglect, as test performance did not always align precisely with prior clinical diagnoses.

**Table 2**

*Patient Responses to Relevant CVSQ Items on Visual Awareness and Functional Deficits*

<b>Patient</b>	<b>Awareness of deficits?</b>	<b>Reading problems?</b>	<b>Bumping into obstacles?</b>
ac	yes	yes	yes
cx	yes	yes	yes
ev	yes	yes	no
ew	yes	no	yes
fe	yes	no	no
hp	no	no	yes
jm	yes	yes	yes
kx	yes	no	no
lo	yes	no	yes
mr	yes	yes	yes
sc	no	no	no
tl	yes	yes	yes
xi	yes	yes	no
zg	yes	yes	yes
zj	yes	yes	yes

**Table 3***Patient-Specific Outcomes on Neuropsychological Measures of Neglect, Memory, and Attention*

Patient	NET				SNT	Extinction		Logical Memory (WMS)			RBMT	WAF	
	Line bisection	Figure copying	Line cancellation	Star cancellation		Acoustic	Tactile	Immediate recall	Delayed recall	Recognition		Intrinsic alertness	Unimodal selective attention
ac	8.5	8.83	10	10	0.022	0	0	9	10	51-75	1	26	28
bs	2	5.5	9	5	-	1	-	10	9	51-75	0	3	3
cx	10	10	10	9.5	0	1	0	11	8	51-75	1	88	61
ev	10	7.67	10	10	0	0	0	5	5	26-50	1	97	6
ew	7.5	10	10	10	0	0	0	10	10	75-100	1	84	28
fe	7.5	8.83	10	9.5	-0.073	-	0	9	9	75-100	0	96	3
hp	7.5	10	10	10	0	-	0	12	9	17-25	1	66	36
jm	10	10	10	10	0.027	-	0	8	9	51-75	1	32	39
kx	10	8.83	10	9.5	-0.038	0	0	-	-	-	1	41	20
lo	10	6.5	10	10	0.032	1	0	13	10	51-75	0	30	-
mr	6.5	8.83	10	9.5	-0.073	0	0	5	5	10-16	0	15	23
sc	7.5	8.83	9.5	7.5	0.036	1	0	12	10	51-75	1	9	16
tl	10	8.83	10	10	0.014	0	0	7	8	3-9	0	96	43
xi	8.5	10	10	9.5	-0.135	0	0	4	1	3-9	0	16	40
zg	10	10	10	10	0.035	0	0	-	-	-	1	NA	59
zj	7.5	10	10	8.5	-0.182	0	0	-	-	-	0	9	9

*Note.* NET subtest scores range from 0 to 10. For the figure copying sub-task, the average for all three drawings (each with a maximum score of 10) is provided. The SNT single task is reported as the Center of Cancellation (CoC) score, ranging from -1 to +1, with values near +1 indicating severe left-sided neglect and

values near -1 indicating severe right-sided neglect. Distributed omissions result in values near 0. The SNT test was not conducted for patient “bs” due to perceived difficulty and clear neglect identified through the NET. Extinction values are coded as 1 (extinction detected) or 0 (not detected). The acoustic extinction test was not conducted for patients “fe,” “hp,” and “jm” due to auditory deficits (hearing aid use), and the tactile extinction test was omitted for patient “bs” due to left hemiplegia. Logical memory tests report age-related scale score equivalents (range: 1–19) for immediate recall and percentiles for the recognition subtest. Patient “kx” did not complete this test due to language barriers, and data are missing for patients “zg” and “zj.” The RBMT screening score is coded as 1 (all five faces recognized without false positives) or 0 (otherwise). Percentiles are provided for WAF intrinsic alertness and unimodal selective attention, with scores of 16–84 considered average, below 16 as below average, and above 84 as above average. Patient “lo” did not complete the unimodal selective attention subtest due to fatigue.

### ***Training feasibility***

Out of the 23 patients allocated to training, 3 dropped out during the first training phase due to perceived technical difficulties, yielding a completion rate of 87%. The remaining 20 patients completed each of the training phases they received. This suggests that the training program was largely well-received and feasible for most participants. Adherence to the training protocol was excellent, with all patients completing the recommended 20 days of training.

In terms of training difficulty, the level achieved by patients on the final day of each phase provides insight into their experience. For the first phase (placebo), participants trained at levels ranging from 1 to 39, with an average final-day level of 23.07 and a standard deviation of 12.77. In the second phase (EMT), the range was 8 to 40, with an average of 28.2 and a standard deviation of 11.12. In the third phase (HMT), the range was 5 to 40, with an average of 26.71 and a standard deviation of 11.66. Given that the same stimuli were used across all phases, it is likely that the EMT phase was perceived as somewhat easier. The device and settings were consistent, and the stimuli were simply distributed on both sides of the VR environment. In contrast, the HMT phase likely presented a higher difficulty due to the switch from the Daydream to the Oculus Go headset and the larger environment that needed to be explored.

According to qualitative feedback, some patients noted a minor inconvenience with the Daydream headset. The head strap would loosen over time, leading to a blurry image, and had to be tightened during training. One patient reported significant discomfort due to the blurriness. Another patient noted that target objects appeared larger and distorted depending on the viewer's position, which could be attributed to the spherical nature of the VR environment. Aside from these inconveniences, there were no major adverse effects reported, and overall, the training experience was well tolerated by most participants.

### ***Effects of training: Primary outcome measure***

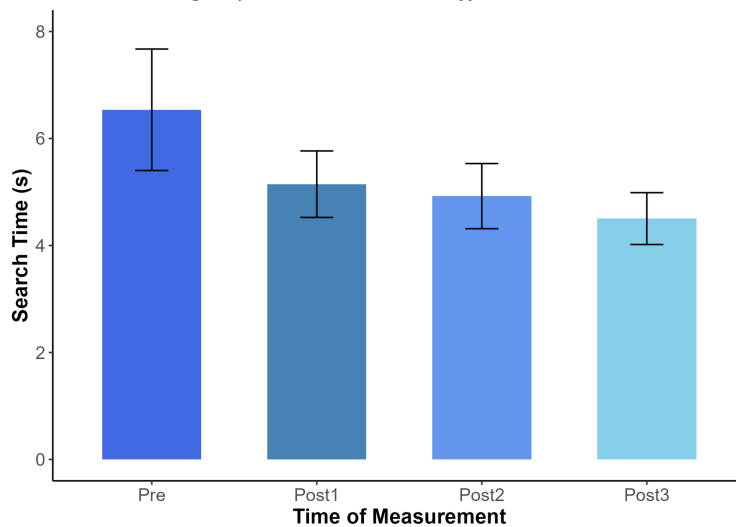
Three main hypotheses were tested regarding the effects of training: (1) EMT would improve visual search outcomes more than placebo training, (2) the addition of HMT might further enhance performance beyond EMT alone, and (3) the combined effects of EMT and HMT would result in greater improvements compared to placebo training. These comparisons aimed to clarify the distinct and cumulative contributions of each training phase.

### Search time

Search times were analyzed for correct, target-present trials to examine how long it took participants to locate the target. Descriptive results, presented in *Figure 9*, reveal a reduction in search time following each training phase, with the most notable decrease occurring after placebo training. It is important to note that the sample size for the final measurement timepoint ( $N = 11$ ) was smaller than at previous timepoints ( $N = 16$ ), as fewer patients completed the HMT.

**Figure 9**

*Average Search Times in Correct, Target-present Trials at Different Measurement Times*



*Note.* Pre = pre-training measurement; Post1 = measurement after placebo training; Post2 = measurement after EMT; Post3 = measurement after HMT. Without extreme outlier “lo”.  $N = 10$  for Post3,  $N = 15$  for all other time points. Error bars represent  $\pm 1$  standard error of the mean (SEM).

When analyzing the isolated effects of placebo training compared to EMT, no significant statistical difference in search time was found. Differences were computed between pre-training and post-placebo measures, as well as between post-placebo and post-EMT measures. Absolute differences were then compared using a one-sided Wilcoxon test (hypothesizing that the post-EMT difference would be greater than the post-placebo difference). The results for all data ( $N = 16$ ) showed no significant difference ( $z = -2.60, p = 0.99$ ). When outliers were excluded, the result remained non-significant ( $t(13) = 2.27, p = 0.98$ ). In descriptive statistics ( $N = 14$ , excluding outliers “lo” and “zj”), the average decrease in search time post-Placebo was 789 ms ( $SD = 1.31$  s). Post-EMT, the decrease was smaller, with an average reduction of 129 ms ( $SD = 796$  ms). This indicates a trend contrary to expectations, with placebo training leading to greater improvement in search times than EMT.

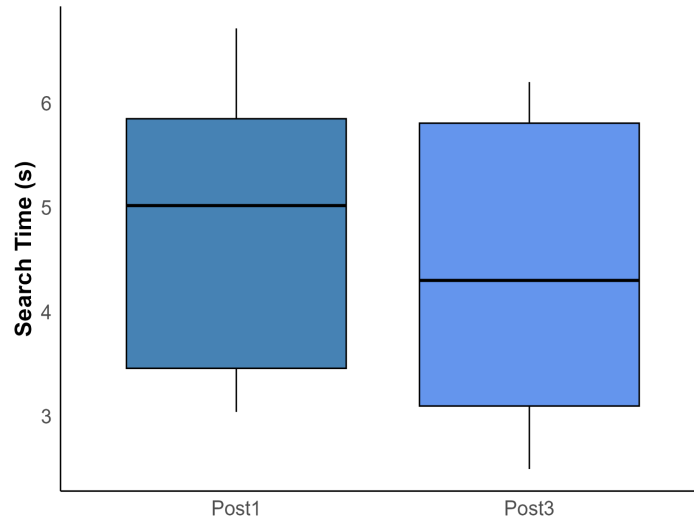
To compare the isolated effects of EMT and HMT, differences were computed between post-placebo and post-EMT measures, as well as between post-EMT and post-HMT measures. Absolute differences were analyzed using two-sided paired-sample t-tests (or their non-parametric equivalent), as it was uncertain whether adding head and eye movement training (HMT) would result in further improvements beyond EMT alone. The results ( $N = 11$ ) showed no significant difference,  $z = -1.27$ ,  $p = 0.89$ . After excluding outliers (“bs” and “lo”), the results remained non-significant ( $t(8) = 0.12$ ,  $p = 0.91$ ). In terms of descriptive statistics ( $N = 9$ , excluding outliers), the average decrease in search time post-EMT was 329 ms ( $SD = 809$  ms) in this sample, compared to the search time after placebo training. After HMT, search time decreased further by an average of 202 ms ( $SD = 826$  ms).

To evaluate the cumulative effects of both exploration training phases (EMT and HMT), performance after HMT was compared to performance after placebo training, with EMT preceding HMT. A one-sided paired-sample t-test (or its non-parametric equivalent) was used for this comparison, hypothesizing that the two training phases together would improve visual search performance relative to placebo training. The results for all data ( $N = 11$ ) showed a significant improvement ( $z = 2.25$ ,  $p = 0.01$ ,  $r = 0.68$ ). When outliers (“bs” and “lo”) were excluded, the result was marginally non-significant ( $t(8) = 1.69$ ,  $p = 0.06$ ). In terms of descriptive statistics ( $N = 9$ , excluding outliers), the average search time decreased from 4.81 seconds ( $SD = 1.20$ ) post-placebo to 4.27 seconds ( $SD = 1.44$ ) post-HMT. A visual representation is shown in *Figure 10*. Given the significant difference in search times between Post3 (i.e. after the two training phases) and Post1 (i.e. after placebo training), we also analyzed overall accuracy to assess any potential speed-accuracy trade-off. The results revealed no significant difference in accuracy ( $z = 0.87$ ,  $p = 0.19$ ), suggesting that the decrease in search time did not come at the expense of accuracy.

Given the 789 ms average decrease in search time for all targets after placebo training, an additional, exploratory analysis was conducted for targets on the blind side. A one-sided Wilcoxon signed-rank test ( $N = 16$ ) found no significant difference in search time improvement between placebo and EMT conditions ( $z = -2.30$ ,  $p = 0.98$ ). Excluding outliers (“bs” and “lo”) yielded similar results ( $N = 14$ ,  $z = -1.76$ ,  $p = 0.96$ ). However, participants were 980 ms faster on average after placebo training ( $N = 14$ ,  $SD = 2.73$  s), while the improvement after EMT was smaller ( $M = 604$  ms,  $SD = 1.25$  s). This, again, suggests a trend in the opposite direction than expected, with placebo training showing greater improvement in search time than EMT, even for targets on the blind side. A visual representation is shown in *Figure 11*.

**Figure 10**

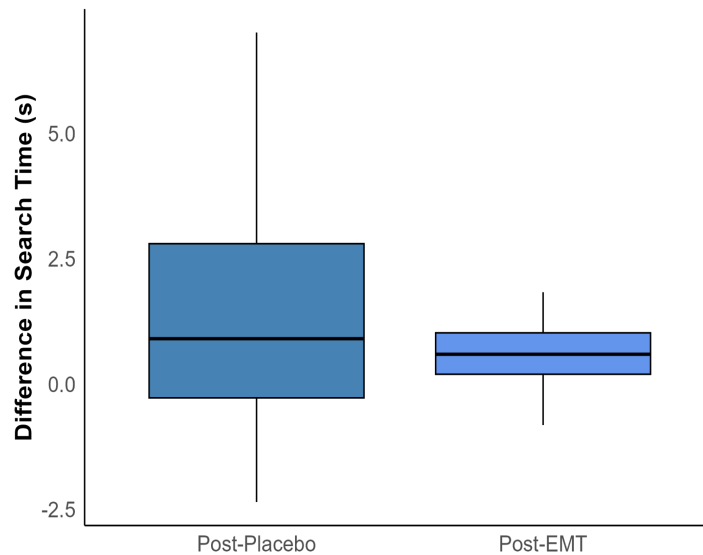
*Average Search Time after Placebo Training and after Two Exploration Training Phases*



*Note.* Search time in correct, target-present trials. N = 9, outliers “lo” and “bs” excluded using the IQR method. Post1 = measurement after placebo training. Post3 = measurement after HMT.

**Figure 11**

*Average Search Time for Targets on the Blind Side after Placebo Training and after EMT*



*Note.* Search time in correct, target-present trials with targets presented on the blind side. N = 12, outliers “bs”, “cx”, “lo” and “xi” excluded using the IQR method. Post-Placebo = difference in search times between Post 1 (after placebo training) and Pre (before placebo training) measurement. Post-EMT = difference in search times between Post 1 (after placebo training) and Post 2 (after eye movement training). Positive values indicate faster search, negative values indicate slower search.

For accuracy in trials with targets on the blind side, the difference between placebo and EMT was also not significant. A one-sided Wilcoxon signed-rank test ( $N = 16$ ) found no significant difference in accuracy between the two conditions, testing the hypothesis that EMT would lead to larger differences than placebo training ( $z = -1.56, p = 0.94$ ). When outliers (“bs”, “lo”, “zj”) were excluded ( $N = 13$ ), the difference remained not significant ( $z = -2.14, p = 0.98$ ). On average, participants were neither more nor less accurate after placebo training ( $N = 13, M = 0.00, SD = 12.84$ ), while they were 1.88% more accurate after EMT ( $SD = 6.74$ ). These findings suggest that although search times for blind side targets tended to improve after placebo training, this was not accompanied by an increase in accuracy.

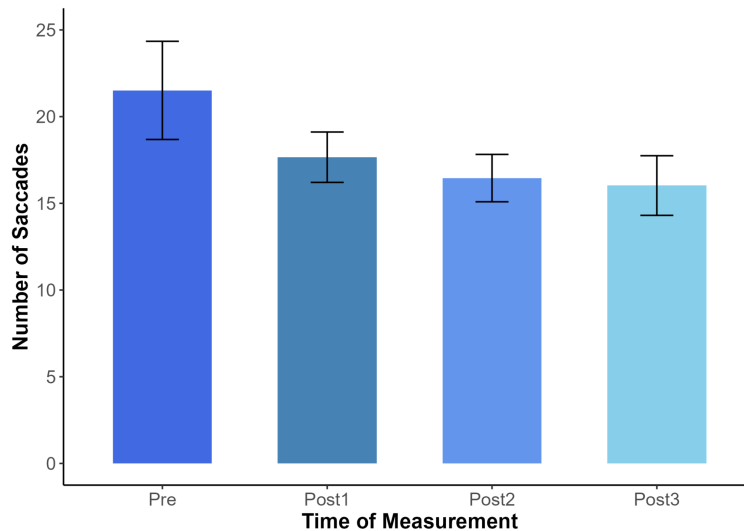
### ***Effects of training: Secondary outcome measures (oculomotor variables)***

#### *Number of saccades*

The number of saccades was analyzed for correct, target-present trials to examine how many saccades it took participants to locate the target. Descriptive results (see *Figure 12*) reveal a reduction in the number of saccades following each training phase, similar to the pattern for search times, with the most notable decrease occurring after placebo training.

**Figure 12**

*Average Number of Saccades in Correct, Target-present Trials at Different Measurement Times*



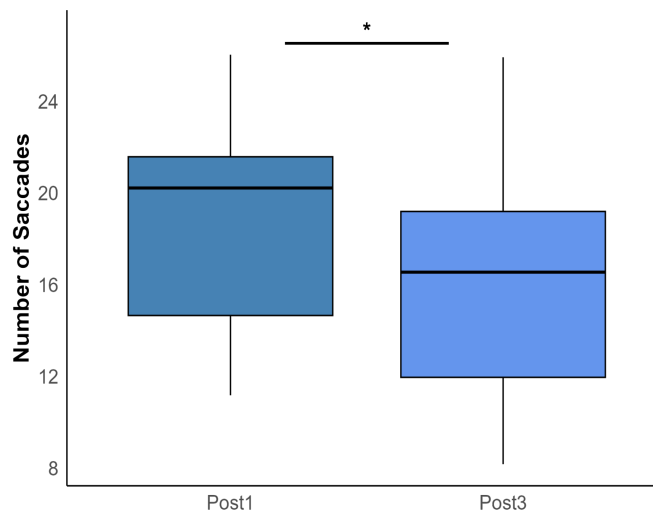
*Note.* Number of saccades in correct, target-present trials only. Pre = pre-training measurement; Post1 = measurement after placebo training; Post2 = measurement after EMT; Post3 = measurement after HMT. Without extreme outlier “lo”.  $N = 10$  for Post3,  $N = 15$  for all other time points. Error bars represent  $\pm 1$  standard error of the mean (SEM).

However, a Wilcoxon signed-rank test comparing placebo and EMT conditions revealed no significant difference ( $N = 16$ ;  $z = -1.51$ ,  $p = 0.93$ ). When outliers (“lo” and “zj”) were excluded ( $N = 14$ ), the comparison remained non-significant ( $z = -0.86$ ,  $p = 0.80$ ). Participants made fewer saccades on average after placebo training ( $M = -2.07$ ,  $SD = 3.86$ ). After EMT, participants also made fewer saccades, but the reduction was smaller ( $M = -1.01$ ,  $SD = 2.73$ ). A comparison of the number of saccades between EMT and HMT found no significant difference between the two conditions with ( $z = -\infty$ ,  $p = 1$ ) or without the outlier “lo” ( $t(9) = -0.58$ ,  $p = 0.57$ ). Participants made fewer saccades on average after both EMT and HMT. Specifically, the average decrease in the number of saccades after EMT was  $-1.62$  ( $SD = 3.00$ ), and after HMT, there was an additional decrease of  $-1.21$  ( $SD = 3.82$ ).

The cumulative effect of both exploration trainings on the number of saccades was assessed by comparing the post-placebo with the post-HMT performance, revealing a significant reduction in the number of saccades after HMT with ( $z = 2.25$ ,  $p = 0.012$ ,  $r = 0.68$ ) and without outlier “lo” ( $t(9) = 2.02$ ,  $p = 0.036$ ,  $d = 0.64$ ). On average, participants made 18.95 saccades ( $SD = 5.39$ ) after placebo training and 16.02 ( $SD = 5.44$ ) after HMT, which followed EMT. These results suggest a cumulative effect of the training, with participants making fewer saccades after the second active training phase. A visual representation is shown in *Figure 13*.

**Figure 13**

*Average Number of Saccades after Placebo Training and after Two Exploration Training Phases*



*Note.* Number of saccades in correct, target-present trials.  $N = 10$ , outlier “lo” excluded using the IQR method. Post1 = measurement after placebo training. Post3 = measurement after head movement training. \* $p < 0.05$

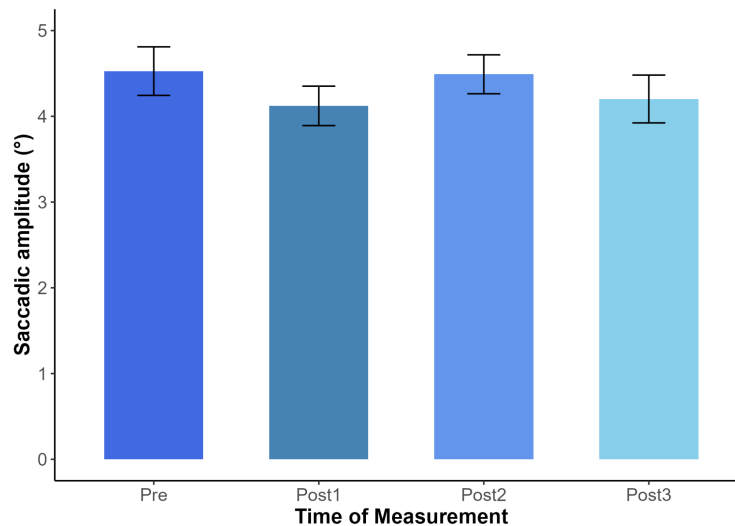
### *Saccadic amplitude*

Saccadic amplitude was analyzed for correct, target-present trials. Descriptive results (see *Figure 14*) show a decrease in saccadic amplitude following placebo training, which returned to baseline levels after EMT. A subsequent decrease in amplitude was also observed after HMT.

The change in saccadic amplitude after EMT was not significantly greater than the change observed after placebo ( $z = -1.30, p = 0.90$ ). After excluding the outliers (“ew” and “zj”), a paired sample t-test ( $N = 14$ ) also revealed no significant difference ( $t(13) = 1.53, p = 0.92$ ). Descriptively, there was a slight reduction in amplitude after placebo training ( $M = -0.3, SD = 0.46$ ) and a small increase in amplitude after EMT ( $M = 0.27, SD = 0.28$ ).

**Figure 14**

*Average Saccadic Amplitude in Correct, Target-present Trials at Different Measurement Times*



*Note.* Saccadic amplitude in correct, target-present trials. Pre = pre-training measurement; Post1 = measurement after placebo training; Post2 = measurement after EMT; Post3 = measurement after HMT.  $N = 11$  for Post3,  $N = 16$  for all other time points. Error bars represent  $\pm 1$  standard error of the mean (SEM).

A comparison of post-EMT and post-HMT performance revealed no significant differences in the changes in saccadic amplitude between the two conditions ( $t(10) = -1.13, p = 0.285$ ). There were no outliers in the data. Descriptive statistics indicated a slight increase in amplitude post-EMT ( $M = 0.20, SD = 0.27$ ) and a small decrease post-HMT ( $M = -0.01, SD = 0.58$ ).

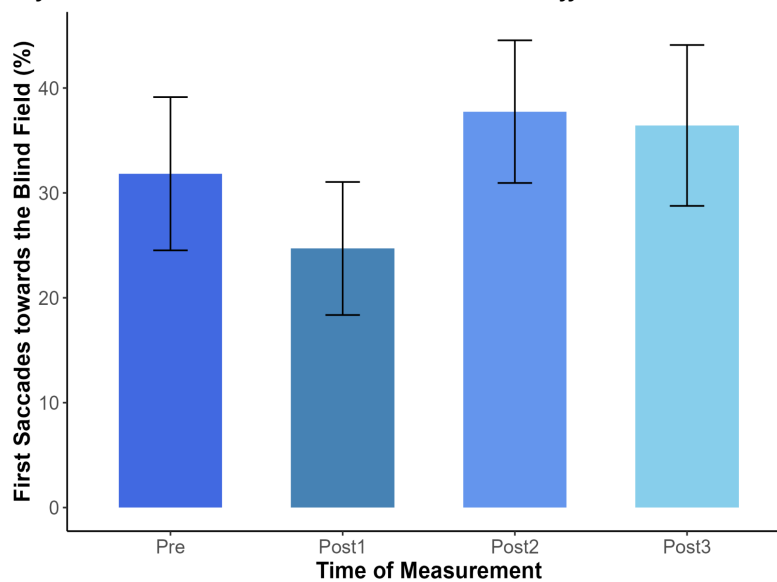
The cumulative effect of both exploration trainings on the number of saccades was assessed by comparing the post-placebo with the post-HMT performance with a paired samples t-test ( $N = 11$ ), which showed no significant difference ( $t(10) = -1.23, p = 0.123$ ). Descriptive statistics indicated a slight increase in amplitude from the post-placebo ( $M = 4.01, SD = 0.90$ ) to the post-HMT ( $M = 4.20, SD = 0.92$ ) measurement.

#### *Percentage of first saccades towards the blind field*

The percentage of first saccades towards the patients' blind field was analyzed for correct, target-present trials with targets on the blind side. Descriptive results (see *Figure 15*) show a decrease after placebo training, an increase after EMT, and little change after HMT.

**Figure 15**

*Average Percentage of First Saccades towards the Blind Field at Different Measurement Times*



*Note.* Percentage of first saccades towards the patients' blind field in correct, target-present trials with targets on the blind side. Pre = pre-training measurement; Post1 = measurement after placebo training; Post2 = measurement after EMT; Post3 = measurement after HMT.  $N = 11$  for Post3,  $N = 16$  for all other time points. Error bars represent  $\pm 1$  standard error of the mean (SEM).

The change in percentage of first saccades towards the patients' blind field after EMT was not significantly greater than the change observed after placebo ( $z = -0.28, p = 0.61$ ). After excluding the outlier "jm" ( $N = 15$ ), this result remained not significant ( $z = -0.75, p = 0.77$ ). Descriptive results showed that post-placebo, participants made on average 7.56% fewer first saccades towards the blind field ( $SD = 25.51$ ), while post-

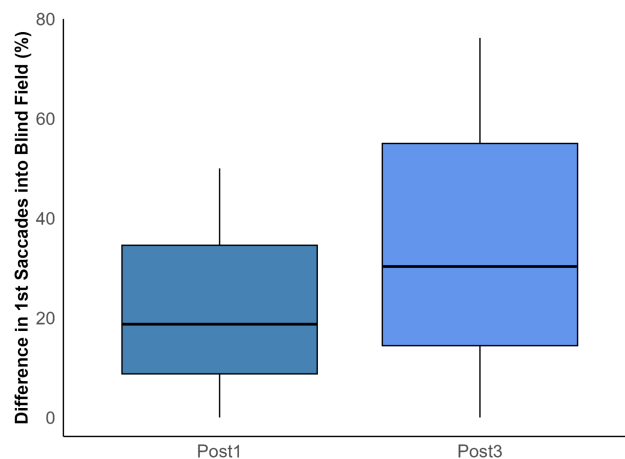
EMT, they made 8.45% more first saccades towards the blind field ( $SD = 18.13$ ) compared to post-placebo levels.

A comparison of post-EMT and post-HMT performance revealed no significant differences in the changes in percentage of first saccades towards the blind field between the two conditions ( $z = -1.82, p = 0.96$ ). There were no outliers in the data. After EMT, participants made on average 6% more first saccades into the blind field compared to post-placebo levels ( $SD = 20.11$ ). After HMT, participants made 1% more first saccades into the blind field compared to post-EMT levels ( $SD = 16.76$ ).

The cumulative effect of both exploration trainings on the number of saccades was assessed by comparing the post-placebo with the post-HMT performance, which showed no significant difference ( $z = 0.82, p = 0.21$ ). After excluding the outlier “lo”, a paired sample t-test ( $N = 10$ ) showed a marginally significant increase in saccades towards the blind field ( $t(9) = -1.52, p = 0.081, d = 0.48$ ). Descriptive statistics indicated that post-placebo, participants made 22.34% of their first saccades into the blind field ( $SD = 17.46$ ), which increased to 34.36% after post-HMT ( $SD = 25.81$ ). These results suggest a tendency for an increase in first saccades towards the blind field following the two training phases. A visual representation is shown in *Figure 16*.

**Figure 16**

*Average Percentage of First Saccades towards the Blind Field after Placebo Training and after Two Exploration Training Phases*



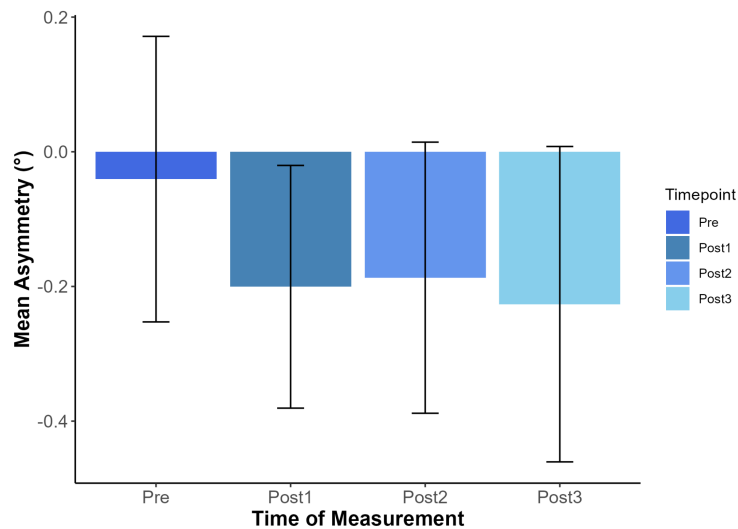
*Note.* Percentage of first saccades towards the patients’ blind field in correct, target-present trials with targets on the blind side.  $N = 10$ , outlier “lo” excluded using the IQR method. Post1 = measurement after placebo training. Post3 = measurement after head movement training.

### Saccadic asymmetry

Saccadic asymmetry, defined as the difference in saccadic amplitude between saccades directed towards the blind and sighted sides, was analyzed for target-absent trials. Descriptive results (see *Figure 17*) showed that asymmetry increased after placebo training, with smaller amplitudes towards the blind field compared to the sighted field, and did not return to pre-placebo levels after two exploratory training phases.

**Figure 17**

*Average Saccadic Amplitude Asymmetry Between the Blind and Sighted Sides at Different Measurement Points*



*Note.* Mean asymmetry between saccadic amplitudes into blind and sighted fields at the different measurement times. Pre = pre-training measurement; Post1 = measurement after placebo training; Post2 = measurement after EMT; Post3 = measurement after HMT.  $N = 11$  for Post3,  $N = 15$  (“zj” had a corrupted file) for all other time points. Negative values = larger saccadic amplitude into sighted field. Positive values = larger saccadic amplitude into blind field. Error bars represent  $\pm 1$  standard error of the mean (SEM).

The change in saccadic asymmetry after EMT was not significantly greater than the change observed after placebo ( $z = 0.97$ ,  $p = 0.16$ ). After excluding the outlier “ew” ( $N = 14$ ), this result remained not significant ( $t(13) = -0.20$ ,  $p = 0.42$ ). The comparison between EMT and HMT also did not reveal a significant difference in changes to saccadic asymmetry,  $t(10) = 0.83$ ,  $p = 0.42$ . There were no outliers in the data. The cumulative effect of both exploration trainings on saccadic asymmetry was evaluated by comparing post-placebo performance with post-HMT performance, showing no significant difference,  $t(10) = -0.55$ ,  $p = 0.29$ . After excluding the outlier “ac”, the results remained non-significant,  $t(9) = -1.12$ ,  $p = 0.14$ .

## ***Effects of training: Exploratory analyses***

### *Loud reading: Words per minute*

Due to the small sample size ( $N = 10$  for the post-placebo vs post-EMT comparison and  $N = 8$  for the post-EMT vs post-HMT comparison), words per minute (*wpm*) were analyzed descriptively. The data revealed that patients could be divided into three categories based on their performance, as shown in *Figures 18 and 19* (blue, red, and grey). Patients in the blue category, who showed improvement after either training phase, tended to have lower *wpm* values at baseline, indicating that those who were slower and less accurate in reading prior to training had more room for improvement. In contrast, patients in the red category were already relatively fluent and accurate during reading prior to training and showed less noticeable improvements.

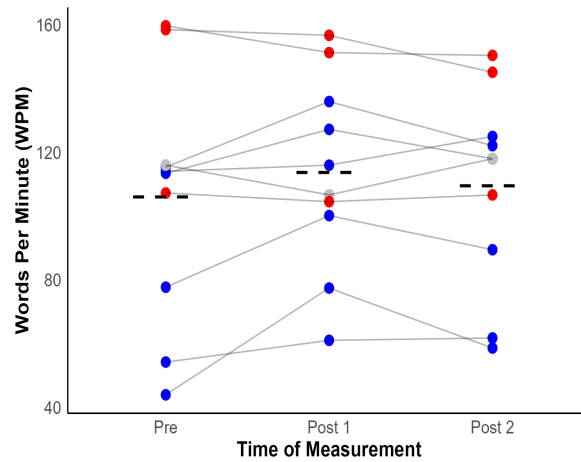
Another pattern observed in the data is that patients with lower *wpm* ( $<100$ ) at baseline tend to have right-sided visual field deficits without macular sparing. Specifically, three out of four patients in this group exhibited right-sided visual field deficits: “xi” (*wpm* = 44) and “mr” (*wpm* = 78) both had right-sided hemianopia, while “zg” (*wpm* = 54) had right lower hemianopia, all without macular sparing. In contrast, among the six patients with *wpm* values greater than 100, four had left-sided visual field deficits: “fe” (*wpm* = 158), “jm” (*wpm* = 116), and “cx” (*wpm* = 113) all had left hemianopia, and “ac” (*wpm* = 114) had left lower quadrantanopia. Of the remaining two patients, “ew” (*wpm* = 160) had right hemianopia but with a large macular sparing, and “hp” (*wpm* = 115) had right paracentral scotomas with central vision mostly intact.

### *Silent reading: Amplitude of rightward saccades*

The amplitude of rightward saccades was analyzed in five participants with right-sided HVFDs ( $N=5$ ), three of whom had data available at all timepoints. Due to the small sample size, the data were analyzed descriptively. The average saccadic amplitude at baseline was  $1.50^\circ$  ( $SD = 0.88$ ), followed by  $1.41^\circ$  ( $SD = 0.70$ ) after placebo training,  $1.37^\circ$  ( $SD = 0.65$ ) after EMT, and  $1.19^\circ$  ( $SD = 0.75$ ) after HMT. *Figure 20* displays the data for each participant, with individual data points and mean values for each timepoint. The data highlight that there was no substantial change in the mean amplitude of rightward saccades across the different measurement points throughout the study.

**Figure 18**

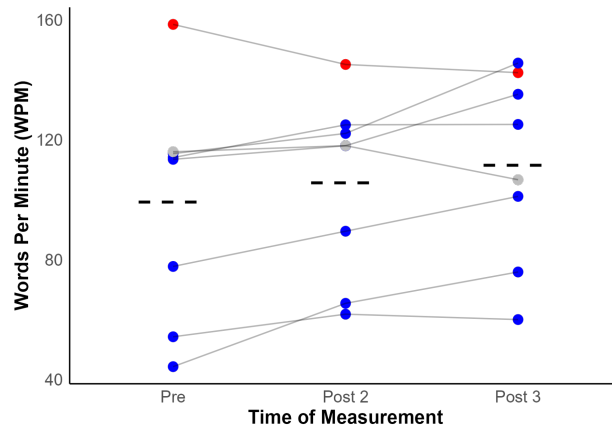
*Words per Minute during Loud Reading: Placebo and EMT comparison*



*Note.* N = 10. Pre = pre-training measurement; Post1 = measurement after placebo training; Post2 = measurement after EMT. Points in blue represent improvement after both training phases (Post 1 > Pre and Post 2 > Pre). Points in red represent decline after training (Post 1 < Pre and Post 2 < Pre). Points in grey represent improvement only after EMT (Post 2 > Pre but Post 1 < Pre). Dashed horizontal lines represent the mean WPM for each timepoint.

**Figure 19**

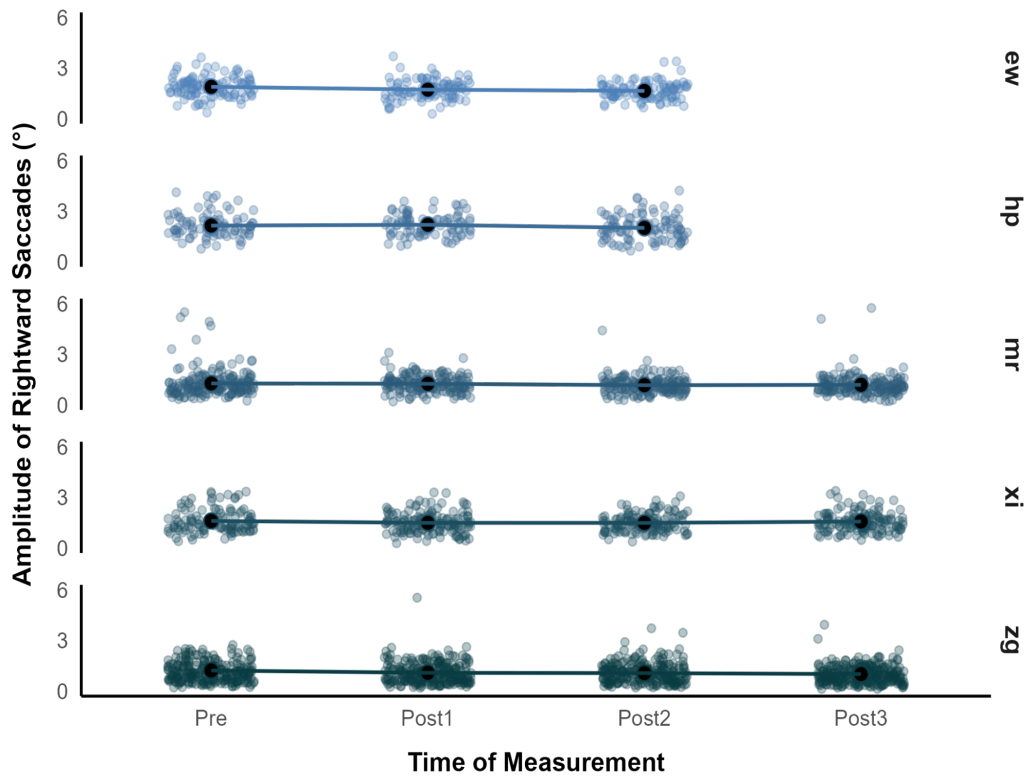
*Words per Minute during Loud Reading: EMT and HMT comparison*



*Note.* N = 8. Pre = pre-training measurement; Post2 = measurement after eye movement training; Post3 = measurement after head movement training. Points in blue represent improvement after both training phases (Post 2 > Pre and Post 3 > Pre). Points in red represent decline after training (Post 2 < Pre and Post 3 < Pre). Points in grey represent improvement only after EMT (Post 2 > Pre but Post 3 < Pre). Dashed horizontal lines represent the mean WPM for each timepoint.

**Figure 20**

*Amplitude of Rightward Saccades Across Timepoints for Five Patients with right-sided HVFDs*



*Note.* Amplitude of rightward saccades for five patients with right-sided HVFDs across four timepoints: Pre = pre-training, Post1 = after placebo training, Post2 = after eye movement training, Post3 = after head movement training. Patient “hp” had a corrupted eye-tracking file at Post3, so his data were excluded. Patient “ew” used a different VR set in the final training phase. Data points represent individual measurements (jittered), with black dots marking the mean amplitude for each participant at each timepoint. Lines connecting the mean values indicate trends across timepoints.

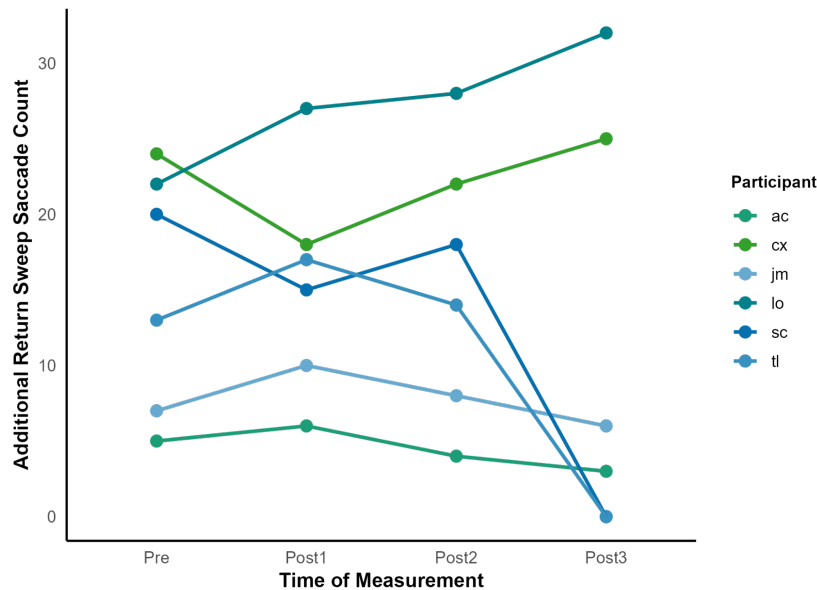
*Silent reading: Number of additional saccades during return-sweep*

The number of additional saccades during return-sweep movements was analyzed in six patients with left-sided HVFDs. Although data were available for seven patients, one (“fe”) was excluded due to poor data quality. Given the small sample size, only descriptive analyses were conducted. At baseline, patients made an average of 15.16 additional return-sweep saccades ( $SD = 8.03$ ). Following placebo training, the mean was 15.50 ( $SD = 7.23$ ), after EMT it was 15.66 ( $SD = 8.89$ ), and after HMT the average decreased to 11.00 ( $SD = 13.91$ ). With two texts silently read per measurement, each containing 16 lines, a mean of 15 additional return-sweep saccades suggests that, on average, an extra saccade occurred approximately every second line. As illustrated in *Figure 21*, four out of six patients exhibited a lower number of

additional return-sweep saccades at the final measurement compared to all previous timepoints. One patient (“cx”) had the same count as at baseline, while another (“lo”) showed an increase in additional return-sweep saccades relative to all prior measurements.

**Figure 21**

*Number of Additional Saccades During Return Sweep Across Timepoints for Six Patients with left-sided HVFDs*



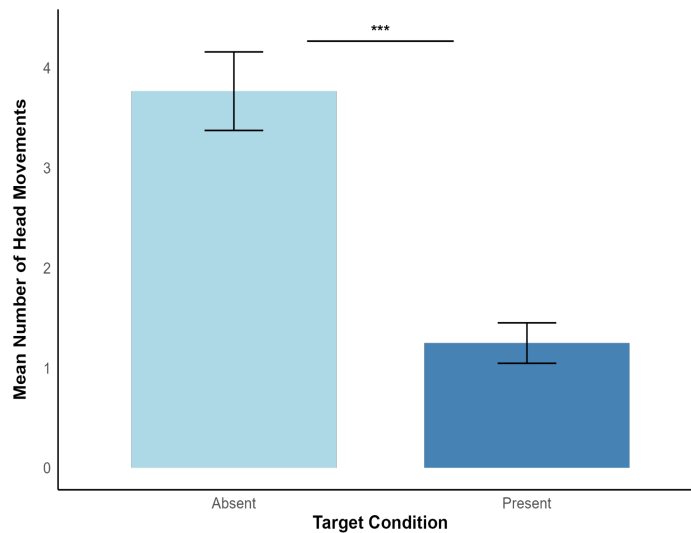
*Note.* Number of additional saccades during return-sweep movements between lines of text. Pre = pre-training, Post1 = after placebo training, Post2 = after eye movement training, Post3 = after head movement training.

*Head movements during HMT*

A paired-samples t-test was performed to compare the number of head movements made by patients during target-present versus target-absent trials, serving as a validation of the head movement segmentation method applied in the analysis. We hypothesized that participants would exhibit more head movements during the target-absent trials. The results confirmed the hypothesis and revealed a significant difference between the two conditions, with participants showing more head movements in the target-absent trials ( $M = 3.77, SD = 1.41$ ) compared to the target-present trials ( $M = 1.25, SD = 0.73$ ),  $t(12) = 8.40, p < .001$ , see *Figure 22*. The effect size, as measured by Cohen's  $d$ , was large ( $d = 2.35$ ).

**Figure 22**

*Number of Head Movements in Target-Present vs Target-Absent Trials*



*Note.* Error bars represent  $\pm 1$  standard error of the mean (SEM). \*\*\*  $p < .001$

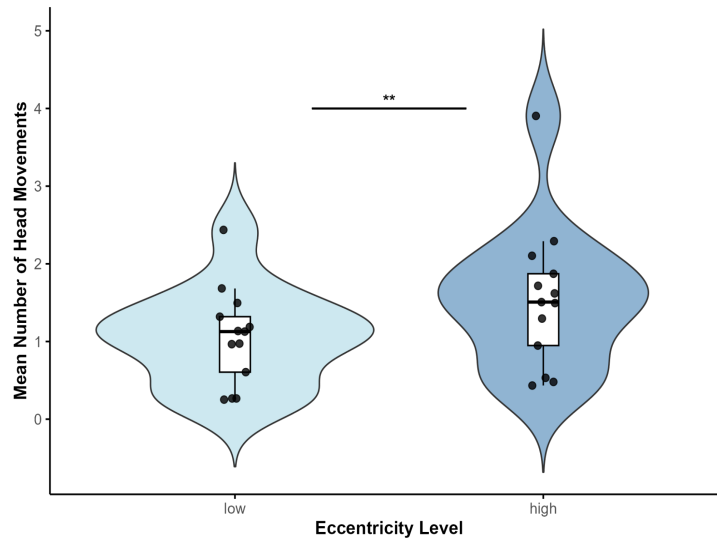
To assess the influence of training progression, which was approximated by increased target eccentricity, on the number of head movements, target eccentricity was categorized into low and high levels based on a quantile split for each participant. A one-sided paired-samples t-test revealed that participants executed significantly more head movements in trials with high horizontal target eccentricity compared to trials with low horizontal target eccentricity,  $t(12) = 3.76, p = .001, d = 1.04$  (see *Figure 23*). When two outliers (participants “jm” and “xi”) were excluded, this effect became even stronger,  $t(10) = 6.29, p < .001, d = 1.89$ . However, a follow-up analysis examining the amplitude of head movements between low and high eccentricity conditions showed no significant difference ( $t(12) = 0.23, p = .41$ ), indicating that while participants increased the frequency of their head movements with higher target eccentricity, the size of the movements did not vary significantly.

To examine whether head movements towards the blind side increased over the course of training, we isolated trials with targets presented on the side of the visual deficit in low versus high eccentricity conditions. Given that the overall number of head movements increased over time, we focused on the mean difference in head movements towards the blind side compared to the sighted side for each patient. A positive difference reflects a higher number of movements towards the blind side. A one-sided paired samples t-test showed that this difference was significantly greater in the high eccentricity condition than

in the low eccentricity condition,  $t(12) = 3.92, p = .001$ , with a large effect size ( $d = 1.09$ ), indicating that participants increasingly oriented towards their blind side as training progressed (see *Figure 24* for a visual representation).

**Figure 23**

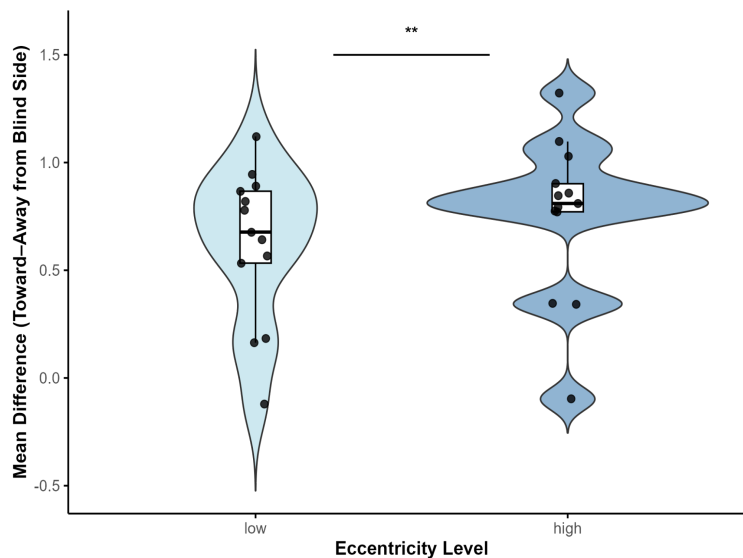
*Number of Head Movements in Trials with High vs Low Horizontal Target Eccentricity*



Note.  $N = 13$ . \*\*  $p = .001$

**Figure 24**

*Head Movement Direction in Trials with High vs Low Target Eccentricity*



Note.  $N = 13$ . \*\*  $p = .001$

## Discussion

### *Training effects*

The primary objective of this study was to investigate the impact of three distinct phases of a VR-based visual search training program on oculomotor behavior and performance during visual search and reading tasks in individuals with HVFDs. For the visual search task, outcomes were analyzed statistically across five core measures: search time, number of saccades, saccadic amplitude, the percentage of first saccades directed into the blind field, and saccadic asymmetry. In contrast, reading task outcomes were analyzed descriptively, given the limited sample size.

Our initial hypothesis posited that the EMT phase would lead to significant enhancements in visual search variables relative to the placebo training. However, this hypothesis could not be confirmed. The analysis revealed no statistically significant differences across any of the five visual search outcome measures. In a further step, we examined whether extending the intervention by introducing an HMT phase—designed to stimulate a larger portion of the visual field and promote the use of both eye and head movements to search for targets—would confer additional benefits beyond EMT alone. This, too, did not yield significant effects, as none of the five visual search metrics demonstrated statistically meaningful changes post-HMT. Nonetheless, when we aggregated the impact of both active training phases (EMT and HMT) and compared this combined intervention to the placebo phase alone, significant improvements emerged. Specifically, participants exhibited significantly faster search times and a reduced number of saccades. There was also a trend towards an increased percentage of first saccades directed into the blind field, suggesting a potential shift in oculomotor strategy following the full training protocol.

The small sample size in our study limited the ability to conduct formal statistical analyses on the reading task, preventing firm conclusions about the training effects on reading performance. Nonetheless, the descriptive data revealed trends consistent with known lateralization effects in HVFDs. Participants with right-sided HVFDs, who typically experience greater difficulties when reading left-to-right scripts, showed improvements in reading performance (words per minute) after the final training phase. In contrast, participants with left-sided HVFDs, who generally encounter fewer challenges in reading tasks, performed well even prior to training and exhibited only a slight decline afterward, although their post-training performance remained high. Additionally, left-sided HVFDs demonstrated a reduction in additional return sweep saccades following the HMT phase, suggesting smoother line transitions. However, these patterns may also reflect regression toward the mean rather than true training-induced gains, particularly given

that the VR training primarily targeted visual search and exploration. Since reading relies on more fine-tuned oculomotor control, the extent to which search-based training generalizes to reading remains uncertain. Further research with a larger sample and reading-specific interventions is warranted to clarify these preliminary findings.

While these findings highlight some encouraging effects of the combined training phases, they also raise important questions. Specifically, the lack of significant improvements in visual search outcomes following the EMT and HMT phases individually, warrant closer examination. We initially hypothesized that the placebo training would have no influence on the outcome measures, resulting in no meaningful differences from the pre-training baseline, whereas the EMT phase would yield significant improvements. However, this expectation was not supported by our data. A closer inspection of the descriptive results provides some insight into this discrepancy. Contrary to our assumptions, the placebo training did appear to influence participants' performance: search times were reduced, participants made fewer saccades, exhibited smaller saccadic amplitudes, initiated fewer first saccades into the blind field, and displayed a subtle increase in saccadic asymmetry, characterized by larger saccades directed into the sighted hemifield compared to the blind field. In particular, the placebo training seems to have already driven improvements in search efficiency—namely, faster search times and a reduced number of saccades—thereby leaving limited room for the subsequent training phases to yield further observable benefits on these measures. For other variables, such as saccadic amplitude and the percentage of first saccades directed into the blind field, placebo training led to changes not regarded as beneficial. This may have introduced a competing influence that the EMT had to first counterbalance before additional benefits could emerge. While the EMT phase appeared to partially reverse these unwanted effects, this recovery was not reflected in our statistical analysis. The beneficial influence of EMT in restoring or enhancing oculomotor behavior after placebo training may have been obscured within the framework of our analytical approach. In sum, the fact that placebo training preceded the active training phases for each participant, combined with its unexpected effects on the outcome measures, may have attenuated the apparent impact of the subsequent EMT and HMT phases and reduced the relative magnitude of change attributable to these active interventions.

The observed effects of the placebo training can be attributed to its inherent characteristics as a form of visual search training, in which stimuli initially appear in the sighted field and later become accessible in the blind field. Although intended as a control condition, it still offered some degree of training. At the

beginning of each search trial, all stimuli were positioned within the patients' sighted field, requiring no eye movements into the blind field. However, as patients shifted their gaze into the sighted field during the task, some stimuli entered the blind field, occasionally prompting saccades in that direction. Since the search area was limited in size, these saccades were likely small, which may explain the observed reduction in saccadic amplitude after placebo training.

The decrease in the percentage of first saccades directed into the blind field also aligns with this interpretation. Throughout the placebo training, participants were consistently reinforced to initiate their search by moving their gaze toward the sighted hemifield—the only region where stimuli were presented. This strategy likely became internalized and subsequently transferred to the post-training visual search task. Similarly, the increase in saccadic asymmetry, with larger saccades into the sighted field compared to the blind field, can be explained by the differential "rewards" associated with these eye movements during placebo training: saccades into the sighted field reliably uncovered more stimuli, while saccades into the blind field yielded comparatively fewer visual gains. In essence, the placebo training functioned as a simplified visual search exercise, improving general search performance measures such as search times and number of saccades. However, its one-sided stimulus presentation also inadvertently reinforced search strategies that were less favorable for exploring the blind hemifield. This explains the co-occurrence of general search efficiency gains alongside maladaptive patterns, such as reduced blind field exploration and smaller saccadic amplitudes.

Beyond the structural characteristics of the placebo training itself, other factors may have contributed to the observed post-placebo improvements. One such factor is the repeated exposure to the visual search task itself. The placebo phase, involving a similar two-alternative forced-choice framework, may have further familiarized patients with task demands, despite the visual search task being specifically designed to limit predictability through randomized target positions and trial types. Additionally, a classical placebo effect cannot be ruled out. Participants may have experienced heightened motivation or focused attention simply by engaging in what they perceived as a structured training program. Importantly, participants were unaware that the initial phase served as a control condition, and post-experiment interviews indicated that, apart from one patient, no noticeable differences were perceived between the placebo and EMT phases. It is therefore plausible that participants viewed the placebo phase as a legitimate intervention, which may have increased their engagement and effort, ultimately enhancing their performance during subsequent assessments. In this sense, the placebo training functioned as a true placebo.

The unintended training effects observed in our placebo condition underscore a critical challenge in visual rehabilitation research: the difficulty of designing a truly neutral control condition. Although intended as a neutral baseline, the placebo phase itself functioned as a form of visual search practice, leading to improvements that narrowed the detectable differences between placebo and subsequent training phases. This highlights the broader issue of how control conditions can obscure or inflate treatment effects if not carefully calibrated to avoid overlap with the mechanisms of action being studied. This concern is not unique to visual rehabilitation. For instance, Furukawa et al. (2014) demonstrated in a meta-analysis of psychotherapy trials that treatment effect sizes varied depending on the type of control condition used. While psychological placebos have been suggested as the gold standard for controlling factors such as regression to the mean, natural recovery, Hawthorne effects, and placebo responses, their implementation is often impractical. Consequently, many studies resort to alternative controls, which may inadequately isolate the true effects of the intervention.

A different study design could have addressed these limitations. A randomized controlled trial with one group undergoing the training while an age-matched control group receives no training (i.e., waitlist or delayed-intervention control) but completes equivalent pre- and post-assessments, could help disentangle genuine intervention effects from general learning or habituation to the task environment, while also controlling for spontaneous recovery or compensation. However, Furukawa et al. (2014) caution that waitlist controls might unintentionally introduce nocebo effects by fostering negative expectations during the waiting period, which could inflate the apparent benefits of the active intervention. Alternatively, within-subject repeated measures designs, as used by Kerkhoff et al. (1994) and Pambakian et al. (2004), could be employed to compare performance during trained and untrained periods.

Another valuable comparison could pit VR-based training directly against established interventions such as conventional computer-based compensatory training to clarify the relative efficacy of VR. Such a study could also evaluate how well the benefits of each training generalize to more complex environments, particularly those that demand eye and head movements across larger areas of the visual field—an advantage inherently offered by VR settings. Prior work by Roth et al. (2009) demonstrated that compensatory training outperformed restorative flicker-stimulation in improving saccadic behavior; however, no studies to date have directly compared VR-based interventions against standard computer-based training for individuals with HVFDs.

Lastly, implementing a sham control based on tasks unrelated to visual search—such as the fixation training used as a placebo in Kasten et al. (1998)—could reduce overlap with eye movement training while still keeping participants engaged. Alternatively, including a control group trained on a cognitive task unrelated to visual exploration (e.g., visual attention tasks) could help determine whether observed improvements stem from eye movement-specific mechanisms or more general cognitive engagement. Notably, Lane et al. (2010) found no difference in visual task improvements between compensatory exploration training and a visual attention training that lacked an exploration component, suggesting that visuo-spatial attention is a critical factor in HVFD compensation.

Despite the unintended effects of the placebo training, the full training phases still yielded significant cumulative benefits on participants' performance. Following the placebo phase, the EMT phase led to further improvements in search time and a reduction in the number of saccades, alongside a tendency to increase the percentage of first saccades into the blind field. Importantly, these positive outcomes were maintained throughout the subsequent HMT phase, which did not diminish the gains made during EMT. Contrary to Zihl's (1995a) suggestion that head movements might negatively affect visual scanning, HMT in our study had no adverse impact, suggesting that the combined EMT and HMT sequence effectively enhanced visual search behavior. This sequential approach shares conceptual parallels with the InSight-Hemianopia Compensatory Scanning Training (IH-CST) introduced by de Haan et al. (2015), which trained eye movements first, followed by head movements, to optimize scanning strategies during mobility tasks such as obstacle avoidance. By leveraging the natural sequencing of eye and head movements, IH-CST demonstrated improved detection of peripheral stimuli, as confirmed in a randomized controlled trial using a waiting list control.

However, the role of head movements in hemianopia remains complex. Postuma et al. (2024) reviewed scanning behavior in individuals with hemianopia and found mixed evidence regarding head movement impairments. While some studies reported no differences in head movement frequency or horizontal dispersion compared to individuals with normal vision, others identified reduced head movement amplitudes in the hemianopia group. Likewise, the relationship between head movements and task performance was inconsistent, with some studies showing a positive association between size and frequency of head movements and task performance, while others did not. These findings suggest that the effectiveness of head movements may be context-dependent, likely offering more benefit in mobility-related tasks than in stationary visual search contexts.

During the HMT phase of this study, patients progressively increased their head movements, particularly towards the side of their visual deficit. This suggests that the training design — gradually increasing target eccentricity and the probability of targets appearing on the side corresponding to the blind visual field — was effective in encouraging exploratory head movements. However, it remains unclear whether this learned behavior would transfer to visual tasks outside the training context or whether such increased head movements are actually beneficial for individuals with HVFDs. Some evidence suggests that head movements may be less reliable for locating targets compared to eye movements (Zangemeister et al., 1982), and there is even the possibility that promoting head movements could encourage a maladaptive strategy. Zangemeister et al. (1982) proposed that finding and fixating targets with homonymous hemianopia presents such a complex sensory-motor adaptive challenge that the brain may simplify the task by stabilizing the head to prioritize vision. If this is the case, the head movement training may inadvertently counteract a naturally developed compensatory mechanism. However, no negative effects on visual search performance were observed in our study.

The post-training visual search assessment was conducted with the head fixed, using a computer screen that presented stimuli within a limited visual field, eliminating the need for head movements, which is consistent with findings by Freedman (2008), who showed that head movements play a significant role in gaze shifts only when the visual angle exceeds 20 degrees. To determine whether patients would naturally employ head movements in broader visual tasks, a free-viewing task on a large screen or with stimuli projected on a wall could be used, allowing for spontaneous head movements to be recorded. Although this approach was initiated in the current study, technical challenges with the mobile eye tracker, which measured both eye and head movements, limited the availability and reliability of the data. Future research could explore this avenue further to assess the generalizability of head movement-based visual exploration beyond VR training and evaluate its impact on visual search performance.

### ***Limitations***

Beyond the absence of pre- and post-measurements assessing head movements, this study has several additional limitations that should be considered when interpreting the findings. One key limitation is the lack of follow-up assessments, making it impossible to determine the long-term sustainability of the training effects. Another gap is the absence of measures evaluating whether training effects transferred

to activities of daily living or led to subjective improvements—insights that would have been valuable in assessing the real-world relevance of the intervention.

The study also faced challenges related to its small and heterogeneous sample. Participants varied significantly in impairment severity, as well as in factors such as age and time since lesion onset. A degree of self-selection bias may have contributed to this variability, with highly motivated and less impaired individuals being more likely to participate, while those with multiple comorbidities struggled with training adherence and testing. As a result, the sample was polarized, consisting of both relatively fit individuals and those with severe impairments, likely influencing training outcomes. Furthermore, post-training sample sizes were inconsistent across the three training conditions. Specifically, the third post-assessment included fewer participants than the previous ones. This discrepancy may have introduced a bias, which should be considered when interpreting the results.

A larger sample size would be particularly necessary for analyzing reading outcomes, where further stratification by the side of the HVFD is required to better understand lateralization effects. However, given the practical constraints of a longitudinal study within the scope of a dissertation, achieving such a sample size was not feasible. Additionally, due to the constraints imposed by the COVID-19 pandemic, the study could not afford to be overly strict with inclusion criteria to achieve a more homogeneous sample. Ultimately, these limitations highlight the need for future research with larger, more controlled samples and extended follow-up assessments to better understand the efficacy and real-world applicability of a compensatory visual search training in VR.

### ***Clinical implications and future directions***

The present findings suggest that VR-based visual search training might become a promising alternative to traditional computer-based compensatory interventions for patients with HVFDs. The two active training phases combined resulted in faster search times and fewer saccades—changes that directly address the demands of everyday visual search tasks. These improvements may translate to smoother and more efficient visual scanning in real-world scenarios, such as locating products in a supermarket or navigating crowded environments. Importantly, the increase in first saccades directed toward the blind field indicates that such training can counteract the maladaptive tendency of HVFD patients to deprioritize their impaired side. This has meaningful safety implications, such as reducing the likelihood of missing critical information in the blind field when crossing streets.

The observed resilience against maladaptive patterns, especially after placebo training appeared to reinforce sighted-field biases, further supports the role of structured visual search training in shaping more adaptive oculomotor behavior in clinical populations. On the other hand, the unintended improvements seen following placebo training highlight a critical consideration for clinical trial design. Even seemingly neutral interventions may exert training-like effects, emphasizing the need for carefully chosen control conditions in rehabilitation research. Clinicians and researchers might also consider whether modified versions of placebo interventions could be leveraged therapeutically. For example, a training program presenting stimuli exclusively in the blind field could potentially encourage even greater exploration of the affected side.

Notably, HMT did not impair oculomotor performance during static visual search tasks, alleviating concerns about possible negative interactions between head and eye movements. Instead, the combined approach aligns conceptually with multi-step programs like IH-CST, suggesting that sequential training of both eye and head movements may yield complementary benefits. Additionally, although limited by sample size, preliminary evidence of improved reading speed among participants with right-sided HVFDs points to potential functional benefits in critical daily activities such as reading. Given that reading difficulties can severely impact independence and quality of life, even modest improvements in this domain are clinically relevant.

From a broader perspective, the study underscores the feasibility and tolerance of VR-based rehabilitation for HVFD patients. An important strength of VR as a rehabilitation tool lies in its portability, allowing patients location-independent training, and the capacity to engage larger portions of the visual field than standard computer screens allow. Moreover, the immersive nature of VR likely enhances patient motivation and adherence, as reflected in the high completion rate across all training phases in the current study. By minimizing external distractions, VR creates an optimal setting for focused and sustained rehabilitation. While VR systems involve balancing affordability and technical sophistication, our results demonstrate that effective and feasible interventions are achievable even with relatively cost-efficient headsets.

In summary, this study contributes to the growing body of evidence supporting compensatory training for patients with HVFDs and demonstrates the added value of implementing such interventions in a VR environment. By enhancing search efficiency and promoting adaptive gaze strategies, VR-based EMT and HMT offer a feasible and engaging approach to improving functional vision. The promising outcomes,

coupled with the versatility and accessibility of modern VR technology, highlight its potential for broader clinical application. Future studies aimed at confirming these effects in real-world contexts will be critical in further validating VR as a valuable addition to the rehabilitation toolkit for individuals living with visual field deficits.

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## Appendix

**Table 1**

*Settings for each level of the eye and head movements trainings for a hemianopia patient*

<b>Level</b>	<b>No. of stimuli</b>	<b>Pair 1 (Distractor / Target)</b>	<b>Pair 2 (Distractor / Target)</b>	<b>Target prevalence (% of trials)</b>	<b>No-target prevalence (% of trials)</b>
1	8	red square / red triangle	green circle / green diamond	Blind: 40, Sighted: 40	20
2	10	red square / red triangle	green circle / green diamond	Blind: 40, Sighted: 40	20
3	12	yellow square / yellow triangle	blue circle / blue diamond	Blind: 40, Sighted: 40	20
4	14	Yellow square / yellow triangle	Blue circle / blue diamond	Blind: 40, Sighted: 40	20
5	12	green triangle / green square	red diamond / red circle	Blind: 40, Sighted: 40	20
6	14	green triangle / green square	red diamond / red circle	Blind: 40, Sighted: 40	20
7	16	blue square / blue triangle	yellow circle / yellow diamond	Blind: 40, Sighted: 40	20
8	18	blue square / blue triangle	yellow circle / yellow diamond	Blind: 40, Sighted: 40	20
9	16	blue circle / blue sector	black triangle right / black triangle down	Blind: 40, Sighted: 40	20
10	18	blue circle / blue sector	black triangle right / black triangle down	Blind: 40, Sighted: 40	20
11	20	green diamond/ green square	red circle /red diamond	Blind: 40, Sighted: 40	20
12	22	green diamond/ green square	red circle /red diamond	Blind: 40, Sighted: 40	20
13	20	P mirrored / P	R mirrored / R	Blind: 60, Sighted: 20	20
14	22	P mirrored / P	R mirrored / R	Blind: 60, Sighted: 20	20
15	24	L mirrored / L	M flipped / M	Blind: 60, Sighted: 20	20
16	26	L mirrored / L	M flipped / M	Blind: 60, Sighted: 20	20
17	24	U flipped / U	W flipped / W	Blind: 60, Sighted: 20	20
18	26	U flipped / U	W flipped / W	Blind: 60, Sighted: 20	20
19	28	N mirrored / N	C mirrored / C	Blind: 60, Sighted: 20	20
20	30	N mirrored / N	C mirrored / C	Blind: 60, Sighted: 20	20
21	28	D mirrored / D	E mirrored / E	Blind: 60, Sighted: 20	20
22	30	D mirrored / D	E mirrored / E	Blind: 60, Sighted: 20	20
23	32	F mirrored / F	Q mirrored / Q	Blind: 60, Sighted: 20	20
24	34	F mirrored / F	Q mirrored / Q	Blind: 60, Sighted: 20	20
25	32	Y flipped / Y	Z mirrored / Z	Blind: 80, Sighted: 10	10
26	34	Y flipped / Y	Z mirrored / Z	Blind: 80, Sighted: 10	10
27	36	S mirrored / S	V flipped / V	Blind: 80, Sighted: 10	10
28	38	S mirrored / S	V flipped / V	Blind: 80, Sighted: 10	10

<b>29</b>	36	star (upside down) / star	heart (upside down) / heart	Blind: 80, Sighted: 10	10
<b>30</b>	38	star (upside down) / star	heart (facing down) / heart	Blind: 80, Sighted: 10	10
<b>31</b>	40	moon (open right) / moon (open left)	trapezoid (upside down) / trapezoid	Blind: 80, Sighted: 10	10
<b>32</b>	42	moon (open right) / moon (open left)	trapezoid (upside down) / trapezoid	Blind: 80, Sighted: 10	10
<b>33</b>	40	cross (tilted) / cross	arrow (left) / arrow (right)	Blind: 80, Sighted: 10	10
<b>34</b>	42	cross (tilted) / cross	arrow (left) / arrow (right)	Blind: 80, Sighted: 10	10
<b>35</b>	44	pentagon (upside down) / pentagon	pacman (open right) / pacman (open left)	Blind: 80, Sighted: 10	10
<b>36</b>	46	pentagon (upside down) / pentagon	Pacman_right / pacman_left	Blind: 80, Sighted: 10	10
<b>37</b>	44	Landolt C (tilted) / Landolt C	yellow-blue triangle / blue-yellow triangle	Blind: 80, Sighted: 10	10
<b>38</b>	46	Landolt C (tilted) / Landolt C	yellow-blue triangle / blue-yellow triangle	Blind: 80, Sighted: 10	10
<b>39</b>	48	pentagram (flipped) / pentagram	cube (left side view) / cube (right side view)	Blind: 80, Sighted: 10	10
<b>40</b>	50	pentagram (flipped) / pentagram	cube (left side view) / cube (right side view)	Blind: 80, Sighted: 10	10

*Note.* Number of stimuli, stimulus pairs, and percentage of trials with targets in the blind or sighted field as well as target-absent trials for each training level. In placebo training, targets appeared in the sighted field in 60% of trials, while 40% of trials were target-absent.

## II. Evaluating the Efficacy of Combined Reading and Exploration Training in Simulated Hemianopia

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## **Abstract**

Homonymous hemianopia, commonly caused by stroke, results in profound deficits in reading and visual exploration. Compared to healthy controls, patients with hemianopia demonstrate prolonged search times during visual exploration tasks, slower reading speeds, and altered oculomotor behaviors, such as reduced saccadic amplitudes and increased re-fixations. These functional impairments often persist due to the lack of effective compensatory strategies, highlighting the necessity for targeted training or therapy. Compensatory therapy approaches have shown promise; however, the extent to which they facilitate transfer effects between visual exploration and reading remains unclear. This study introduces a novel combination training that integrates both visual exploration and reading elements and examines its efficacy in healthy participants with simulated hemianopia. To ensure that our simulation accurately reflects real-world deficits, we first confirmed that simulating right-sided hemianopia impaired all reading and exploration metrics as expected. A control group received exploration training without text-based stimuli. Both training types resulted in significant improvements in most visual exploration and reading measures. Notably, combination training yielded greater gains in reading performance than exploration training alone, emphasizing the added value of incorporating text-based stimuli. These findings support the potential advantages of combination training, which warrants further investigation in clinical populations. If validated, this approach could optimize therapy outcomes for patients with hemianopia while reducing the time and resources required for rehabilitation.

## **Introduction**

### ***Homonymous hemianopia***

Approximately 20–30% of neurorehabilitation patients have visual field defects, with homonymous hemianopia being the most common (Kerkhoff, Münssinger, & Meier, 1994; Rowe et al., 2013). This condition results from lesions in the postchiasmal visual pathways, causing loss of either the left or right half of the visual field in both eyes, depending on the lesion's location in the brain (Goodwin, 2014; Zihl, 2003). Due to the crossing of nasal retinal fibers at the optic chiasm, a lesion on one side leads to contralateral visual field loss (Zihl, 2003). Most lesions are located in the occipital lobe (45–54%) or along the visual pathways (23–32%) (Zhang et al., 2006a, 2006b).

Stroke is the primary cause of homonymous hemianopia, affecting 20–57% of survivors, with incidence rising to 70% in cases involving the posterior cerebral artery (Goodwin, 2014; Rowe et al., 2009; Pambakian, Currie, & Kennard, 2005). Other causes include subarachnoid hemorrhage, intracerebral hematomas, brain injuries, tumors, and, less commonly, brain surgery, demyelinating diseases, and congenital conditions (Zhang et al., 2006a). The etiology of homonymous visual field deficits varies by age; in children, traumatic brain injuries (34%) and tumors (27%) are the most common causes, unlike vascular events in adults. With the increasing prevalence of vascular diseases in older populations, hemianopia is far more frequent in adults and rare in children and adolescents (Goodwin, 2014; Kedar et al., 2006).

Homonymous visual field deficits significantly impact individuals' ability to lead independent and active lives, causing challenges in daily activities, reduced social participation, and diminished quality of life (Gall et al., 2009). These impairments manifest as difficulties with spatial awareness, reading, navigation, and visual exploration, often leading to increased risks of injury and reduced driving ability. Additionally, they are associated with heightened risks of depression and social isolation (Bergsma et al., 2012; Goodwin, 2014; Jones & Shinton, 2006; Rowe et al., 2009). The following sections will focus on the areas of visual exploration and reading, as these abilities are both commonly affected and critical to overall functioning.

### ***Visual exploration in hemianopia***

We explore our visual environment through eye movements that bring relevant stimuli onto the fovea for recognition, enabling healthy individuals to quickly and efficiently assess their surroundings (Zihl, 1999). In hemianopia, a lack of sufficient oculomotor exploration often hinders object detection in the blind hemifield and the ability to gain a visual overview. This can lead to everyday challenges such as collisions,

falls, and difficulties with orientation (de Haan et al., 2015; Jones & Shinton, 2006; Zihl, 1999). Patients with homonymous hemianopia demonstrate distinctive eye movement and search patterns in visual search tasks, significantly differing from those of healthy individuals. Compared to a healthy control group, these patients exhibit longer search times, increased number of saccade and fixations, smaller saccadic amplitudes, and longer, less systematic search paths, often with re-fixations (Machner et al., 2009; Pambakian et al., 2000; Zihl, 1995b, 1999).

However, not all patients with homonymous hemianopia exhibit these visual search impairments. Zihl (1995b) found that about 40% of patients displayed search patterns comparable to those of healthy individuals. Many patients develop compensatory strategies over time, including staircase, overshoot, and predictive approaches. Initially, patients may use the staircase strategy, making multiple stepwise saccades to locate a target. Later, they may adopt the more efficient overshoot strategy, involving a single large saccade that surpasses the target, followed by a corrective drift or reverse saccade. The predictive strategy emerges when the object's location is consistent; after using the staircase or the overshoot approach to find it initially, patients memorize its position and execute a single targeted saccade in future attempts (Meienberg, 1988; Meienberg et al., 1981).

The extent to which effective, long-term spontaneous compensation in eye movements occurs in homonymous hemianopia remains controversial. Reinhard et al. (2014) found reduced saccadic accuracy in the blind hemifield, with patients often performing overshooting or undershooting saccades. The frequency of these dysmetric saccades showed no correlation with age or disease duration, leading the authors to argue for short-term compensatory mechanisms rather than long-term adaptation. Machner et al. (2009) observed spontaneous improvement in visual search patterns (reduced search time, fewer saccades, and more structured search paths) in only one of nine patients during an 18-month follow-up. These findings suggest that while spontaneous compensatory mechanisms are possible, they persist in only a small fraction of patients. The challenges of spontaneous compensatory mechanisms in visual exploration for patients with homonymous hemianopia highlight the broader difficulties in adapting to visual field loss, which also affects other tasks, such as reading.

### ***Reading in hemianopia***

Reading is a complex process. For the purpose of our study, we can distinguish between linguistic aspects (such as semantics and syntax of sentences) and visual aspects. Rayner (1998) and Schotter et al. (2012) describe the oculomotor basis of reading, where eye movements consist of rapid saccades spanning 7–9 letters, interspersed with brief fixations. During saccades, visual sensitivity is suppressed (Matin, 1974), preventing the perception of new information. Fixations allow foveal perception and efficient processing of text content. Fixation duration depends on how easily a word is processed. About 30% of words are skipped without being foveally fixated. Importantly, understanding a sentence does not require every word to be foveally processed (Rayner, 1998; Schotter et al., 2012). Additionally, reading in healthy individuals relies on recognizing whole words rather than synthesizing individual letters (Leff et al., 2000; Glezer et al., 2009).

Since foveal processing is essential for recognizing written words, even a small scotoma in this central area can significantly impair reading (Trauzettel-Klosinski, 2002). In homonymous hemianopia, macular sparing—where central vision within 1° to 10° of the visual field remains intact—can occur (Horton et al., 2021; Leff, 2004). Macular sparing is attributed to the dual blood supply of the occipital lobe, primarily from the posterior cerebral artery and partly from the middle cerebral artery's temporo-occipital branch, as well as to the macula's large cortical representation (Goodwin, 2014). The extent of preserved central vision affects both fixation patterns and reading performance. Specifically, a macular sparing of more than 5 degrees was shown to be essential for unimpaired reading (Trauzettel-Klosinski & Reinhard, 1998). While the foveal area (0.5°–1°) is typically spared in postchiasmal damage, larger spared regions are rare, with 75% of patients having a sparing of less than 4° (Schuett et al., 2008b).

During reading, parafoveal information (2°–5°) also plays a crucial role in planning forward saccades and ensuring fluent reading (Beh et al., 2023; Leff et al., 2000). Parafoveal perception influences reading by modulating the processing of the currently fixated word through the parafovea-on-fovea effect and by aiding the processing of the next word, which is partially perceived and processed parafoveally before fixation, known as the preview benefit (López-Pérez et al., 2016). In left-to-right scripts like English, the perceptual span gained from parafoveal processing extends about 14–15 characters to the right of fixation and only 3–4 characters to the left (Rayner et al., 2009, 2010; McConkie & Rayner, 1976). For right-to-left scripts such as Hebrew, the span shifts accordingly, being larger to the left of fixation (Pollatsek et al.,

1981). Hence, this asymmetry is shaped by reading direction and likely modulated by attentional processes.

The asymmetry of the perceptual span relative to reading direction causes left-to-right readers with right-sided homonymous hemianopia to experience more severe difficulties than those with left-sided hemianopia (Goodwin, 2014; Leff et al., 2000; Schuett, 2009; Schuett et al., 2009b; Trauzettel-Klosinski, 2002; Trauzettel-Klosinski & Reinhard, 1998; Zihl, 1995a). This condition, known as hemianopic alexia, significantly impacts patients' quality of life (Leff & Behrmann, 2008). Left-sided hemianopia primarily affects line transitions during reading, requiring additional saccades during return sweep; most other eye-movements during reading are well-preserved in those cases (McDonald et al., 2006; Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995a). In contrast, right-sided hemianopia leads to broader impairments. While patients can often read individual words well, they generate inefficient saccades along a line of text, with prolonged fixations and increased number of forward and regressive saccades to navigate around the scotoma (Leff et al., 2006; McDonald et al., 2006; Trauzettel-Klosinski, 2002). These individuals also exhibit shorter saccadic amplitudes (Zihl, 1995a). These oculomotor abnormalities result in slower reading speeds and more frequent errors, including omissions (e.g., skipping syllables or words) and guessing errors when attempting to complete partially read words (Schuett, 2009). Such difficulties can affect social participation and create challenges in social settings (Maeyama et al., 2024).

### ***Simulated homonymous hemianopia***

Studying the effects of hemianopia on reading and visual search in real patients can pose challenges due to recruitment difficulties, comorbidities, and high dropout rates. To overcome these challenges, hemianopia can be simulated in healthy participants using a gaze-contingent paradigm, in which one side of the screen is blanked out based on the participant's gaze position (Tant et al., 2002). Studies have shown that participants with simulated homonymous hemianopia exhibit similar eye movement patterns to real patients, such as slower reading speeds, increased forward and regressive saccades, and reduced saccadic amplitudes (Beh et al., 2023). These changes are more pronounced in simulated right hemifield deficits, leading to smaller saccadic amplitudes and more forward-directed saccades, more regressive saccades and slower reading speeds compared to left hemifield deficits and controls. Similarly, participants with simulated deficits demonstrate longer search times during visual search tasks, less systematic scan paths, more fixations, and reduced detection accuracy, paralleling findings in real hemianopia patients (Tant et al., 2002). Moreover, during simple visual search, there is a bias toward

directing saccades to the sighted field, highlighting that healthy participants with simulated hemianopia fail to spontaneously adopt efficient compensatory strategies, favoring saliency even at the cost of search efficiency (Nowakowska et al., 2016). These findings suggest that the visual deficits themselves primarily drive defective scanning behavior.

### ***Rehabilitation of homonymous hemianopia***

Rehabilitation for visual field loss involves three main approaches: substitution, restitution, and compensation. Substitution uses optical aids, such as prism glasses, or environmental modifications to assist patients, restitutive methods aim to partially restore the affected visual field, while compensatory strategies focus on helping patients use intact functions and abilities to mitigate visual deficits (Ajina & Kennard, 2012; Kerkhoff, 2000; Lane et al., 2008; Pollock et al., 2019). Existing studies on hemianopia that evaluate the impact of treatments on activities of daily living are limited in number (Pollock et al., 2019). If early spontaneous remission does not occur within the first few months (Ajina & Kennard, 2012; Goodwin, 2014), restitution of visual function is exceedingly rare (Kerkhoff, 2000; Lane et al., 2008). Among the mentioned approaches, compensatory methods have thus far shown the strongest evidence and best outcomes, making them the most promising for treating hemianopic patients (Bouwmeester et al., 2007; Howard & Rowe, 2018; Kerkhoff, 2000; Lane et al., 2008; Pollock et al., 2019). Typically, compensatory training for exploration and reading is provided as separate programs.

Exploration training is based on the idea that individuals with homonymous visual field deficits can adapt to and compensate for their impairments. This training systematically reinforces compensatory mechanisms, which may also emerge spontaneously, to optimize search strategies and better manage the visual deficit. Patients are typically instructed to rely solely on eye movements rather than head movements, with an emphasis on directing saccades toward the blind hemifield and practicing larger saccadic eye movements to improve speed and efficiency in regaining a visual overview. As training progresses, newly learned strategies can be tested and consolidated in real-life settings (Kerkhoff, 2000; Pambakian et al., 2005; Pelak et al., 2007). Compensatory exploration training leads to more efficient search strategies, reflected in reduced reaction times and error rates. It also improves activities of daily living and expands the patient's visual search field, although it does not restore the visual field itself. Importantly, these positive effects remain stable over time (Bouwmeester et al., 2007; Mannan et al., 2010; Nelles et al., 2001; Pambakian et al., 2004; Pelak et al., 2007).

Reading training typically aims to enhance oculomotor skills specific to reading. A recent review indicates that interventions focusing on adjusting saccadic behavior are the most prevalent in hemianopia literature (Tol et al., 2024). Text-based materials such as words or sentences are typically presented for a limited duration (Aimola et al., 2014; Schuett et al., 2012; Zihl, 1995a; Zihl et al., 2021), though Schuett et al. (2008a) emphasize that effective compensatory reading training primarily depends on practicing specific oculomotor movements essential for reading, rather than solely using text-based materials. In some cases, patients are instructed to first fully perceive the presented words (Schuett et al., 2012; Zihl, 1995a) or to shift their gaze toward the portion of the word located in the blind hemifield (Zihl, 1995a; Zihl et al., 2021) before reading aloud. The goal is to train more precise and efficient steering of visual attention while helping patients optimize saccadic amplitude and fixation duration (Maeyama et al., 2024). An alternative compensatory approach involves reading text that scrolls from right to left across the screen. Gradually increasing the scrolling speed induces small-field optokinetic nystagmus, which has been shown to improve subsequent reading performance on normal static text (Spitzyna et al., 2007).

Through compensatory reading training, patients achieve better reading performance, marked by faster reading speeds and fewer errors (Aimola et al., 2014; Maeyama et al., 2024; Zihl et al., 2021). Improvements in oculomotor parameters are also observed, with reduced number and duration of fixations as well as increased saccadic amplitude (Maeyama et al., 2024; Zihl, 1995a). Patients with right-sided hemianopia generally require more training sessions than those with left-sided hemianopia to achieve similar reading improvements (Kerkhoff, 2000; Zihl, 1995a). Overall, compensatory reading training has been shown to produce long-lasting positive effects (Kerkhoff, 1999; Zihl et al., 2021).

Studies on compensatory reading and exploration training for hemianopia show varying results in terms of session duration. Jacquin-Courtois et al. (2013) found that even a single session with 300 trials of compensatory exploration training led to faster search times in hemianopia patients. On the other hand, Ludwig and Schenk (2021) observed that repeated application of a gaze-contingent intervention over three consecutive days, designed to reduce an ipsilesional exploration bias, resulted in more pronounced and lasting effects compared to a single session. Zihl et al. (2021) reported a 40–45% improvement in scanning and reading performance after training, with noticeable benefits early on; however, both reading and exploration skills plateaued after 10–12 sessions. Schuett's review (2009) suggests that between 7 and 25 hours of compensatory training can lead to stable, clinically significant improvements. Together, these findings indicate that while initial improvements can be achieved with minimal training, sustained progress typically requires repeated sessions.

Few studies have explored potential transfer effects between exploration and reading training in patients with hemianopia or healthy participants with simulated hemianopia. Existing research shows these trainings are task-specific: exploration training improves search abilities without enhancing reading, while reading training boosts reading performance without affecting exploration (Lane et al., 2010; Schuett et al., 2012; Zihl et al., 2021; Postuma et al., 2023). This lack of transfer likely reflects differing oculomotor demands. Reading requires small, precise horizontal saccades, whereas exploration involves large, multidirectional saccades (Aimola et al., 2014; Schuett et al., 2012).

Most studies on compensatory therapies for hemianopia focus on either visual exploration or reading training in isolation. Aimola et al. (2014) addressed this gap by combining both components in a single study, aiming to enhance both skills simultaneously. Participants completed up to 14 daily blocks of tasks, randomly alternating between reading and visual exploration exercises. The exploration tasks required identifying a target stimulus among distractors, while the reading tasks involved locating a pseudoword among real words arranged on a horizontal line. The combined training improved both exploration and reading abilities. However, the specific contribution of each training component (reading vs. visual exploration) to the overall improvement remains unclear.

### ***Study objective and hypotheses***

The present study takes a further step by evaluating the effectiveness of a combined training approach for simulated hemianopia. Unlike standard visual exploration training, this method uses a single task type to simultaneously improve both reading and exploration skills. By addressing two key deficits at once, this approach could offer an efficient, timesaving, and resource-effective neuropsychological therapy for hemianopia. The computer-based training is designed for independent use at home without the need for direct therapeutic supervision.

Involving healthy participants with simulated hemianopia allows for the examination of training effects directly related to visual deficits, free from confounding comorbidities. This approach also facilitates the collection of preliminary data from a larger sample, informing decisions on subsequent patient-based training evaluations. The primary objective is to determine whether a combined training program, integrating reading and exploration components, enhances reading and visual exploration performance in simulated hemianopia, compared to exploration-only training. Based on existing research, we anticipate that while both training methods improve reading and exploration abilities, the combined

approach leads to greater enhancements in reading. Additionally, increasing the number of training sessions is anticipated to further augment training-related improvements.

## **Methods**

### ***Participants***

42 healthy participants (32 female, mean age: 25.45, range: 18 to 53,  $SD = 6.76$ ) with normal or corrected-to-normal vision completed the experiment in exchange for 10€ per hour or course credit.<sup>1</sup> The majority of participants were students (83.33%), achieved a university entrance qualification as their highest level of education (64.28%), had normal vision (57.14%) and were right-eye dominant (69.04%).

Participants were both randomly assigned to each training group and equally distributed between the two groups, resulting in each group comprising 21 participants. *Table 1* illustrates that no significant differences were observed between the participants in the exploration and the combination groups with regards to gender, education level, occupation, visual acuity and eye dominance.

All participants gave informed written consent to participate in the study, which was approved by the local ethics committee (Department of Psychology, Ludwig Maximilian University of Munich). Exclusion criteria encompassed psychiatric disorders, motor impairments affecting the dominant arm, reduced unaided visual acuity, and diseases of the eye. Each of the participants was required to confirm with their signature that none of the above applied to them. Furthermore, due to the use of German language stimuli in the study, only native German speakers (including bilingual speakers) could be included.

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<sup>1</sup> It should be noted that initially we tested 46 participants. Four participants had to be excluded due to difficulties with eye-tracking calibration and the resulting impossibility of an accurate gaze-contingent procedure.

**Table 1***Comparative analysis of descriptive data between the two training groups*

Variables	Participants		
	CT group (n = 21)	ET group (n = 21)	Group comparison
<b>Mean age (SD)</b>	27.23 (7.70)	23.66 (5.26)	W = 301, p = 0.04
<b>Gender, n (%)</b>			$\chi^2(1) = 0.00, p = 1.00$
Female	16 (76.19)	16 (76.19)	
Male	5 (23.80)	5 (23.80)	
<b>Level of education, n (%)</b>			$\chi^2(2) = 1.04, p = 0.59$
Academic degree	7 (33.33)	7 (33.33)	
University entrance qualification	14 (66.66)	13 (61.90)	
Secondary school diploma	0	1 (4.76)	
<b>Occupation, n (%)</b>			$\chi^2(2) = 3.00, p = 0.22$
Student	18 (85.71)	18 (85.71)	
Working full-time	1 (4.76)	3 (14.28)	
Working part-time	2 (9.52)	0	
<b>Visual acuity, n (%)</b>			$\chi^2(1) = 0.09, p = 0.75$
Normal	11 (52.38)	13 (61.90)	
Corrected-to-normal	10 (47.61)	8 (38.09)	
<b>Eye dominance, n (%)</b>			$\chi^2(1) = 0.00, p = 1.00$
Left	7 (33.33)	6 (28.57)	
Right	14 (66.66)	15 (71.42)	

*Note.* CT = combination training, ET = exploration training.

**Apparatus**

Stimuli were created with MATLAB R2015a (MathWorks, Natick, MA) and the Psychophysics Toolbox Version 3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) and presented on a 532x299 mm monitor at 144 Hz. Gaze position was recorded using a table-mounted Eyelink 1000 Plus system (SR Research,

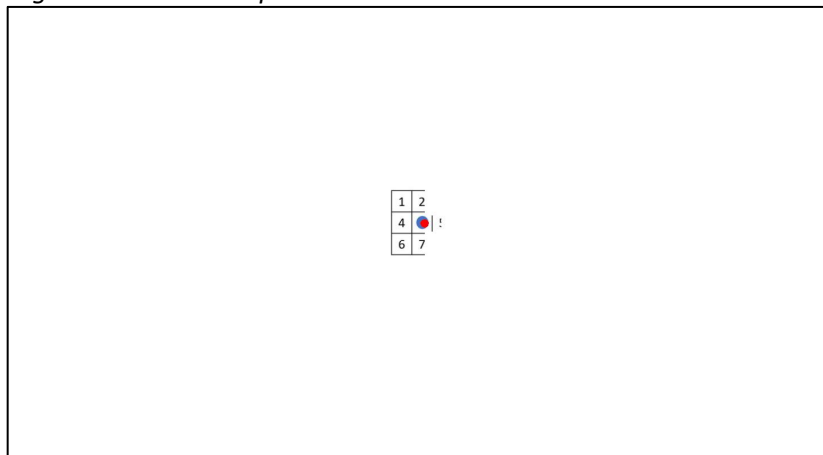
Mississauga, Ontario, Canada) at a temporal resolution of 2000 Hz. To minimize head movements and increase eye tracking accuracy, participants placed their head on a chin rest. The distance between the eye and the upper part of the screen was 705 mm and 750 mm between the eye and the lower part of the screen. In the beginning of each experiment, a 9-point calibration procedure, involving black rings against a white background, was conducted and repeated as needed. Calibration was deemed successful when the deviation between calibration and validation remained equal to or below 1° visual angle for each point. The dominant eye was used for eye tracking, shifting to the non-dominant eye only when calibration yielded insufficient data quality.

### ***Hemianopia simulation***

We simulated right-sided hemianopia in all participants. This choice was made considering that reading impairment tends to be more pronounced in right-sided hemianopia compared to left-sided hemianopia (Leff et al., 2000; McDonald et al., 2006; Trauzettel-Klosinski, 2002; Zihl, 1995a), thus allowing for a better investigation of training effects on reading performance. We also simulated a 2° macular sparing based on findings from a prior pilot study, which revealed that reading under this condition was feasible, albeit with sufficient impairment to illustrate potential training effects. Hemianopia was simulated through a gaze-contingency paradigm, wherein stimuli located on the right of a participant's gaze position were continuously concealed by a white mask that seamlessly integrated into the white background (see *Figure 1*).

**Figure 1**

*Illustration of the Right-Sided Hemianopia Mask*



*Note.* The red circle indicates the current gaze position. To the right of this point, the screen is obscured by a hemianopia mask matching the background color, with a rectangular 2° area of macular sparing.

### **Study design & procedure**

Visual search and reading abilities were assessed at five different times across four consecutive days (see *Figure 2*). On the first day, we assessed visual search and reading performance without simulating hemianopia (*Baseline*). Subsequently, both tasks were repeated with simulated hemianopia (*Pre*). For days two, three and four, the procedure was consistent: participants completed three training units of either exploration or combination training followed by assessments of visual search and reading performance (*Post 1, Post 2, Post 3*). Thus, the present study is a randomized controlled trial that combines between-subject (to assess differences between training groups) and within-subject (to assess differences across the five testing times) designs.

**Figure 2**

*Overview of the study procedure for each participant*

Day 1	Day 2	Day 3	Day 4
<b>Baseline</b> VST & REA	<b>Training</b> 3 parts	<b>Training</b> 3 parts	<b>Training</b> 3 parts
<b>Pre</b> VST & REA	<b>Post 1</b> VST & REA	<b>Post 2</b> VST & REA	<b>Post 3</b> VST & REA
<b>Duration:</b> ~ 1h	<b>Duration:</b> ~ 1.5h	<b>Duration:</b> ~ 1.5h	<b>Duration:</b> ~ 1.5h

*Note.* VST = visual search task. REA = reading task.

### *Visual search task*

Participants had to search for a slightly tilted line (target) among vertical lines (distractors), as illustrated in *Figure 3*, and indicate target presence with the first button on the button box and target absence with the second. The target stimulus was present in half of the trials, with random order of target-present and target-absent trials. The visual search task comprised 96 trials plus ten practice trials, which were repeated if the accuracy fell below 60%. Participants received feedback on their response accuracy only after practice trials; no feedback was given thereafter.

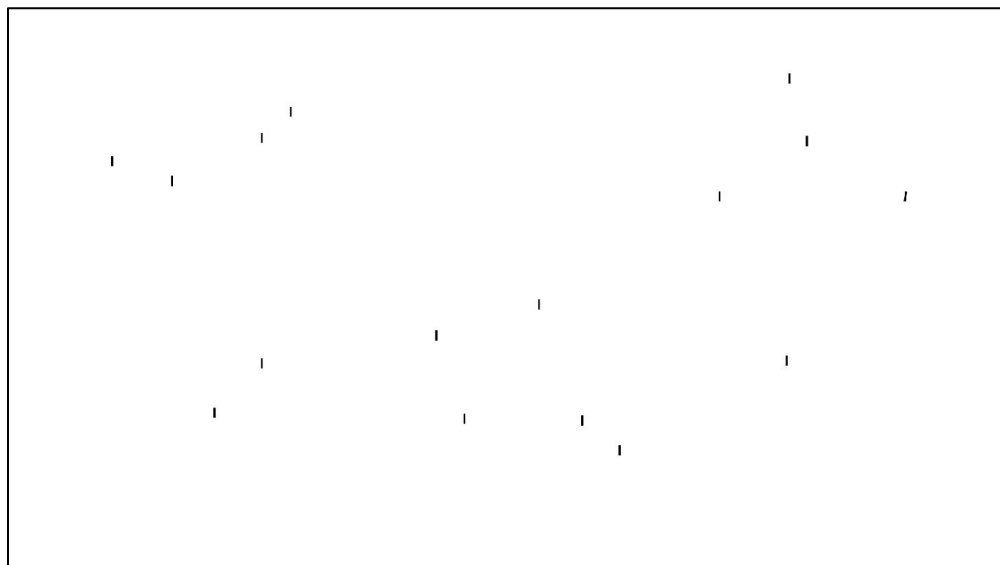
There was a total of 16 stimuli in each trial. All stimuli were black, measured 0.5° and were presented on a white background. Stimulus positions were defined by a grid system with three eccentricity levels and

four quadrants. Distractors were equally distributed across these dimensions, with random positions in each trial. The target appeared across eccentricity levels and quadrants with equal frequency, although at random positions each time.

Each trial began with an 800 ms fixation period using the fixation target shape recommended by Thaler et al. (2013) to check the calibration. The fixation target was 1° in diameter. If the gaze position drifted beyond a 2° x 2° window surrounding the fixation target, the calibration procedure was repeated. Subjects were instructed to always start their search from screen center, where the fixation target was presented. There was no limit on the stimulus presentation time. After participants provided their response, the display disappeared, followed by a 1000 ms blank display (inter-trial period).

### Figure 3

#### *Visual Search Task*



*Note.* Target-present trial in the visual search task. The target was a tilted line, while the distractors were straight lines.

#### *Reading task*

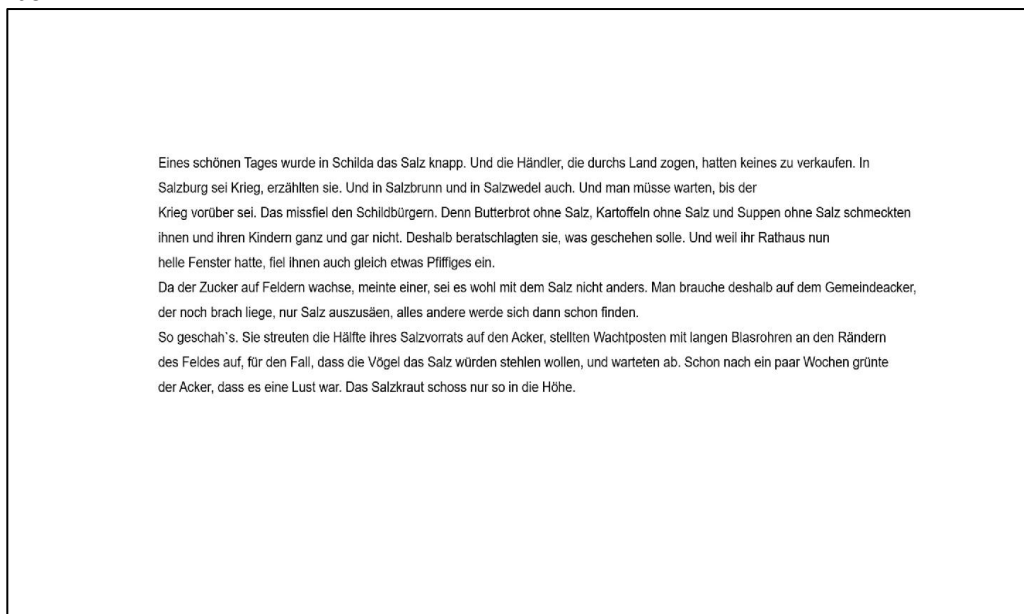
To measure reading ability, three texts were presented in succession with the first text being read aloud and the other two being read silently. The loud reading was recorded with an audio recording device. Participants were instructed to read the texts presented on the screen as quickly and as accurately as possible and to signal their completion via button press. After reading each text participants were asked

two content-related binary (yes-no) questions by the experimenter, which aimed to ensure that the texts were read and not simply looked at.

There were different versions of the reading task, each with three different texts, for each of the five outcome measurement time points, resulting in a total of fifteen different texts. The five different versions were distributed randomly across participants and time points. Six texts used are part of the Saarbrücker Lesetest (SBL, Kerkhoff, Wimbauer & Reinhart, 2015) and were selected because they have a narrative style, do not require prior knowledge and are not widely known. As these six texts were not sufficient, further nine texts were taken from the story collection "*Geschichten von den Schildbürgern*". The number of words, structure and style of these texts were very similar to those from the SBL. All texts were largely identical in length, with 179 to 182 words distributed over nine to eleven lines. The font used was Arial with a font size of 24. The texts were left-aligned, had a line spacing of 1.5 and presented across the entire screen. An example text is shown in *Figure 4*.

**Figure 4**

*Reading Task*



Eines schönen Tages wurde in Schilda das Salz knapp. Und die Händler, die durchs Land zogen, hatten keines zu verkaufen. In Salzburg sei Krieg, erzählten sie. Und in Salzbrunn und in Salzwedel auch. Und man müsse warten, bis der Krieg vorüber sei. Das missfiel den Schildbürgern. Denn Butterbrot ohne Salz, Kartoffeln ohne Salz und Suppen ohne Salz schmeckten ihnen und ihren Kindern ganz und gar nicht. Deshalb beratschlagten sie, was geschehen solle. Und weil ihr Rathaus nun helle Fenster hatte, fiel ihnen auch gleich etwas Pfiffiges ein.

Da der Zucker auf Feldern wachse, meinte einer, sei es wohl mit dem Salz nicht anders. Man brauche deshalb auf dem Gemeindeacker, der noch brach liege, nur Salz auszusäen, alles andere werde sich dann schon finden.

So geschah's. Sie streuten die Hälfte ihres Salzvorrats auf den Acker, stellten Wachtposten mit langen Blasrohren an den Rändern des Feldes auf, für den Fall, dass die Vögel das Salz würden stehlen wollen, und warteten ab. Schon nach ein paar Wochen grünte der Acker, dass es eine Lust war. Das Salzkraut schoss nur so in die Höhe.

*Note.* An example text from *Saarbrücker Lesetest* presented on the screen.

### *General training procedure*

During each training day, a training session comprised three parts, each containing 58 trials, with the initial ten trials serving as practice runs. In the first training part, each trial featured 20 stimuli. In the second part, there were 16 stimuli per trial, and in the third part, there were 12 stimuli per trial. The stimulus length progressively increased from the first to the third training part. The participants had to search for a target among distractors and indicate by button press whether the target was present (first button) or not (second button). The target was present in half of the trials.

For each training group, stimuli were pseudo randomly arranged on the screen. However, each stimulus configuration had to satisfy the additional constraint that stimuli were not presented in adjacent positions. This constraint should ensure that large saccadic eye movements in various directions were required to locate the target. Prior to the training, participants were briefed on its purpose: to enhance compensatory eye movements to mitigate visual field loss. They were instructed to promptly and accurately scan the screen for a target and to respond rapidly by using the button box. The experimenter also emphasized, multiple times if needed, the importance of searching the "blind" area of the screen first unless the target was already clearly visible.

Throughout the training, subjects received immediate feedback following each trial in the form of an auditory signal: a high-pitched sound for correct answers and a deep sound for incorrect ones. Additionally, after every 10th trial, the screen displayed the percentage of correct trials.

### *Combination training stimuli*

In the first two parts of the combination training, pseudowords were used as distractor stimuli while the target stimulus was a correct German word (excluding first names, colloquial language or loan words). In the first part of the daily training, stimuli consisted of four-letter words, while in the second part, they were six-letter words (see an example trial in *Figure 5*). During the third part of the training, distractor stimuli were syntactically incorrect German sentences, while the target stimulus was a syntactically correct German sentence. Both target and distractor sentences comprised four words, each containing two to four letters. To be able to determine whether a stimulus constituted a correct word or sentence, it needed to be read, which required specific horizontal saccades with smaller amplitudes.

Aspects of the pseudowords and sentences were systematically varied to generate three different distractor types for each correct word and sentence (see examples provided in *Table 2*). For the first part of the training (four-letter words), the first or last letter of the correct word was altered (distractor types 1 and 3, respectively) and the second and third letters were swapped (distractor type 2). For the second part of the training (six-letter words), we interchanged the first and second (distractor type 1), third and fourth (distractor type 2), and fifth and sixth letters (distractor type 3). For the third part (four-word sentences), we modified the word order within the sentence. We conducted a preliminary survey involving our lab colleagues who were not part of the study to validate the newly generated words. The aim was to ensure that correct words were identified as such and pseudowords were recognized as pseudowords. Any stimuli that led to confusion or uncertainty were removed and substituted with more clear-cut alternatives.

Stimulus positions were determined by a grid system with three eccentricity levels and four quadrants. Stimuli were evenly distributed across these dimensions, with random positions in each trial. The target appeared with equal frequency across eccentricity levels and quadrants, with randomized positions.

For each training part, there was a list of 116 target stimuli, with three different distractor stimuli derived from each target stimulus. In target-present trials, targets were randomly selected from the respective list. Distractors, except those derived from the respective target word, were selected from the same list as the target stimulus, with an equal number randomly selected from each of the three distractor categories. In target-absent trials, distractors were exclusively drawn from a single category, maintaining an equal distribution of distractors from each category throughout all such trials.

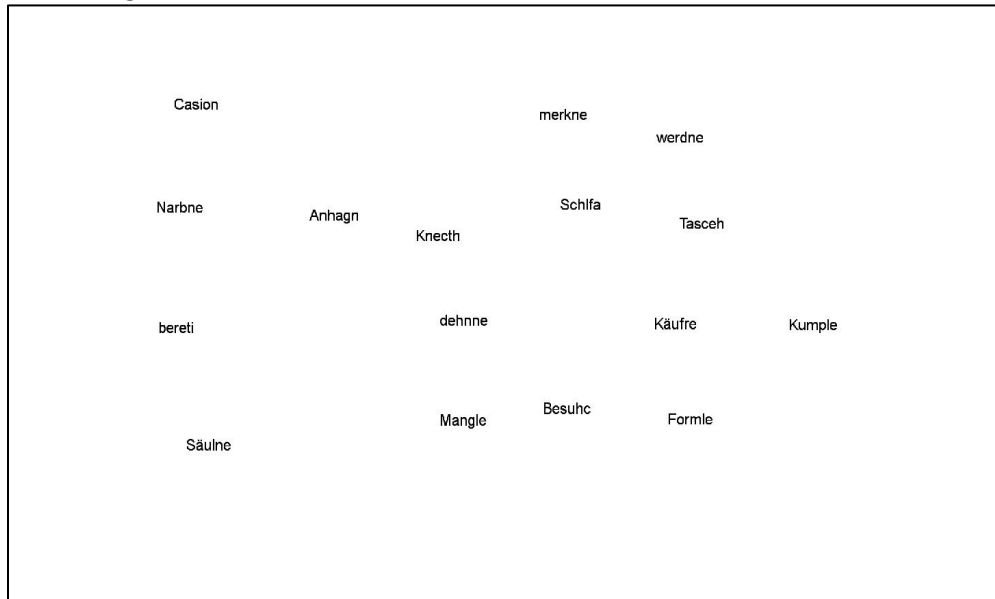
**Table 2**

*Example stimuli generated for each part of the combination training*

<b>Training</b>	<b>Target</b>	<b>Distractor Type 1</b>	<b>Distractor Type 2</b>	<b>Distractor Type 3</b>
<b>Part 1</b>	Auge	Muge	Ague	Augt
<b>Part 2</b>	andere	nadere	anedre	andeer
<b>Part 3</b>	Der Baum ist hoch.	Der hoch Baum ist.	Ist Baum hoch der.	Der Baum hoch ist.

**Figure 5**

*Combination Training*



*Note.* A target-absent trial of part two of the combination training filled with Type 3 distractors.

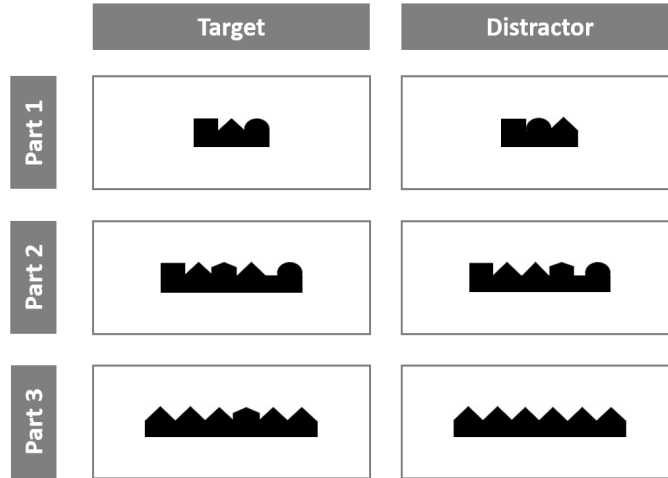
*Exploration training stimuli*

For exploration training, we created so-called "key bit" stimuli, which share similarities in shape and length with words. These stimuli comprise a mix of symbols and require visual scanning to distinguish between distractors and target stimuli. Importantly, there is no strict requirement to read them from left to right; they can also be recognized by right-to-left scanning or by directly searching for their distinguishing features (see the overview of stimuli in *Figure 6*).

The stimuli increased in length as participants progressed from part 1 to part 3 of the exploration training. In part 3, we introduced variability in the position of the distinguishing feature within the target stimulus, rendering it unpredictable. This was intended to encourage structured eye movements, similar to those used in reading, to identify the target. It's important to note that the specific direction of eye movements, such as left-to-right, was still not required. An example of an exploration training trial is depicted in *Figure 7*.

**Figure 6**

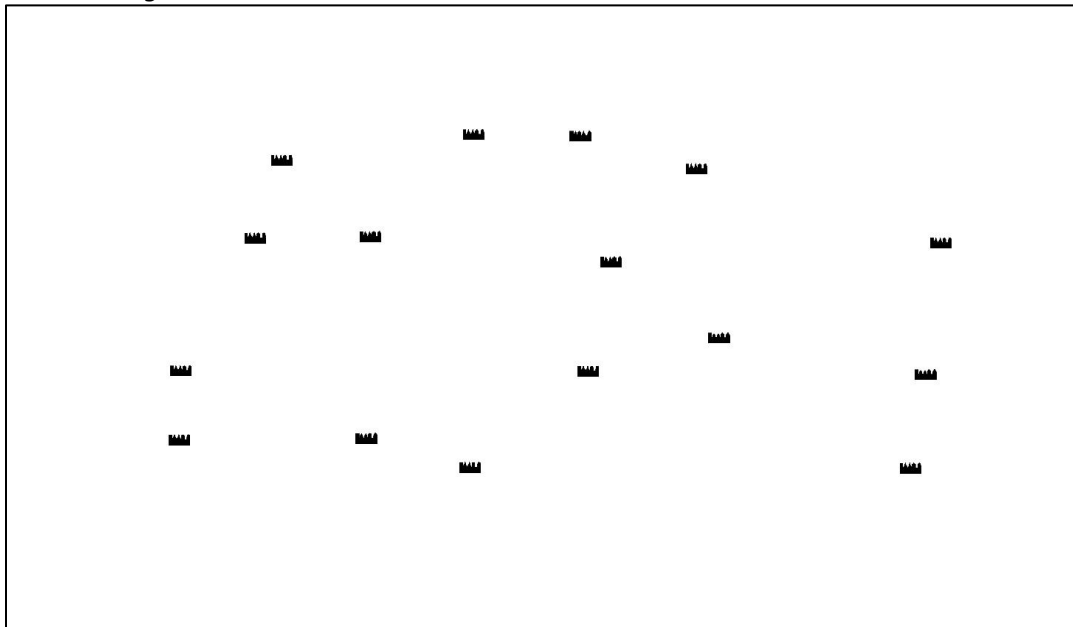
*Overview of target and distractor stimuli in the exploration training*



*Note.* In part 3, the distinguishing feature could appear at different positions within the stimulus (second, third, fourth or fifth positions).

**Figure 7**

*Exploration Training*



*Note.* A target-present trial in the second part of the exploration training.

### **Data analysis**

Data preprocessing, such as extracting information on fixation behavior, was performed using Matlab (Version R2016a). Descriptive and inferential statistics were calculated using R (R version 4.2.0; 2022-04-22). Depending on the specific research question, data were analyzed using either paired-sample or independent t-tests. When the assumptions for parametric testing were violated, non-parametric Wilcoxon tests were applied. Specifically, non-parametric tests were applied when the Shapiro-Wilk test for normality was significant (indicating the data were not normally distributed) and when the Levene's test indicated a lack of homogeneity of variances. However, for comparisons with sufficiently large sample sizes, parametric t-tests were conducted even if the Levene's test was significant. All analyses employed one-sided tests due to the directional nature of the hypotheses, except for analyses on training data. For effect sizes, Cohen's *d* was calculated for t-tests, and the effect size estimate *r* for Wilcoxon tests was derived by transforming the p-value into a z-value and applying the formula  $r = z/\sqrt{N}$ , where *N* is the total sample size (Field et al., 2012, p. 665). Outliers in the loud reading variables were identified and removed using Grubb's test. For the remaining analyses on the silent reading, visual search and training variables, extreme outliers were excluded individually for each planned comparison.

Initially, we aimed to determine whether the simulation of right-sided hemianopia led to the anticipated effects on reading and visual search variables in three ways. First, we compared baseline performance with the first session of simulated hemianopia (pre-training). Key variables of interest for reading included reading duration, number of errors, number of accurately read words per minute (wpm), number of fixations, fixation duration, saccadic amplitude, and number of regressions (approximated as the number of backward saccades within lines). For visual search, the variables examined were search times in correctly completed trials with targets in the blind field (i.e. right side of the screen), accuracy in trials with targets in the blind field, fixation duration, number of saccades until target fixation, saccadic amplitude, and the percentage of first saccades directed toward the blind field (in trials with targets presented in the blind field).

Second, we analyzed reading errors during the reading-aloud task, expecting more errors at the end of words in right-sided hemianopia. Reading errors were categorized into 25 distinct error types. The defined categories (see Appendix, Table 1) are based on error classifications from the *Münchner Leseanalyse* (Mohr & Völker-Munro, 2019) and the *Zürcher Lesetest* (ZLT-II; Petermann & Daseking, 2019). Error types irrelevant to hemianopia were excluded, while those specific to hemianopia were added, adapting the

classification scheme to fit with the specific requirements of hemianopic reading. Each reading-aloud session was recorded as an audio file. Errors were detected and categorized through qualitative analysis of baseline and simulation recordings (pre-training).

Third, we examined whether performance during training, measured by accuracy and search time, varied across three different types of distractors. This analysis focused on the first two parts of the combination training, which in its target-absent trials included systematically adapted pseudo-words, with original words changed either in the beginning (Type 1), middle (Type 2), or end (Type 3). We expected distractor type to influence both search time and accuracy under right-sided hemianopia simulation, with Type 3 leading to poorer performance than Type 1. A Friedman test, followed by Wilcoxon tests for post-hoc comparisons, was used to evaluate these differences due to the non-normal distribution of the data. To confirm that any differences between distractor types were due to the hemianopia simulation rather than general reading tendencies, search time and accuracy during part 2 of the combination training were assessed in a control group of 10 healthy participants (5 female, 5 male; average age = 28 years) with normal or corrected-to-normal vision, who did not undergo the hemianopia simulation.

After assessing the impact of hemianopia simulation on reading and visual search performance, we evaluated training effects by comparing pre-training outcomes to the average of all three post-training sessions within each group. Subsequently, we compared the training groups based on the differences between pre- and post-training conditions (averaged across the three training days). The effects of training duration were explored by comparing outcome measures between the first and second days, as well as between the second and third days, for each group separately. Given the high number of comparisons and the lack of independence between tests, False Discovery Rate (FDR) corrections were applied.

We also analyzed training performance to address two key questions. First, we examined how comparable the two training types were in terms of accuracy and search times, which reflect training difficulty. To assess this, we conducted parametric t-tests or non-parametric Wilcoxon tests (for non-normally distributed data) to compare performance between the two groups across all three parts on both the first and second training days. Second, we investigated how improvements in search time from day 1 to day 2 of training transferred to reading duration and search times during the post-training tasks across training groups. Only participants who improved their search times from the first to the second training day ( $N = 36$ ) were included. Transfer metrics were calculated by comparing the relative change in post-training

reading and search times during the visual search task to the reduction in search time during training, with positive values indicating a loss of gains, negative values suggesting amplification, and values near zero reflecting retention. The two training groups were then compared using a parametric t-test or a non-parametric Wilcoxon test (for non-normally distributed data).

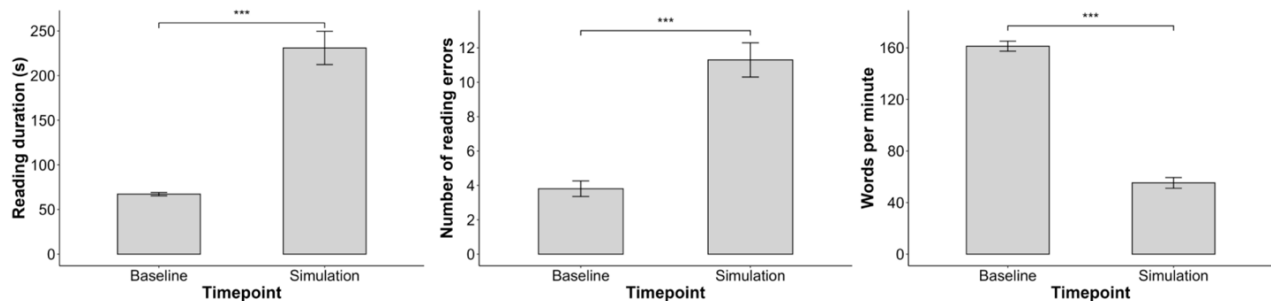
## Results

### Simulation check

To assess whether the simulation of right-sided hemianopia produced the intended effects, we conducted planned comparisons between the baseline and pre-training simulation measurements (i.e., the first session with simulated hemianopia) across all training groups. Each variable of interest was analyzed using one-sided t-tests or Wilcoxon tests, depending on the data distribution. The simulation significantly impacted all reading and exploration variables, confirming the expected effects (see Appendix, *Table 2*). The largest impact of the simulation according to effect sizes was on the variables words per minute ( $t(39) = 18.36, p < 0.001, d = 4.37$ ), fixation duration ( $t(40) = -11.28, p < 0.001, d = 1.76$ ) and search times ( $t(38) = -11.66, p < 0.001, d = 1.87$ ) during visual search. Graphical representation of results is provided in *Figures 8-10*. The change in reading patterns under the simulation condition is also visually evident, with an increased number of fixations, longer fixation durations, and shorter saccades, as shown in *Figure 11*.

**Figure 8**

### Comparison of Reading Variables in the Baseline and Simulation Conditions during Reading Aloud

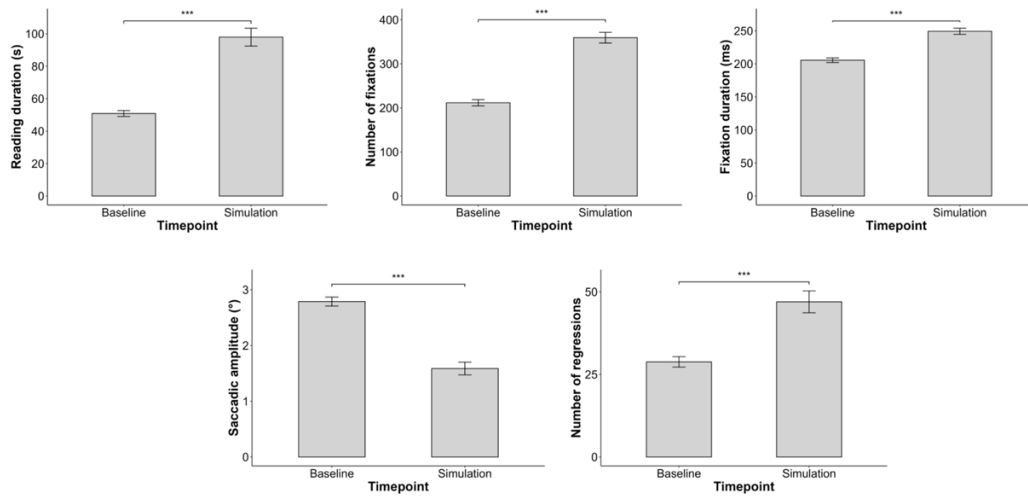


*Note.* Error bars represent  $\pm 1$  standard error of the mean (SEM). All tests were one-sided.

\*\*\* $p < .001$ .

**Figure 9**

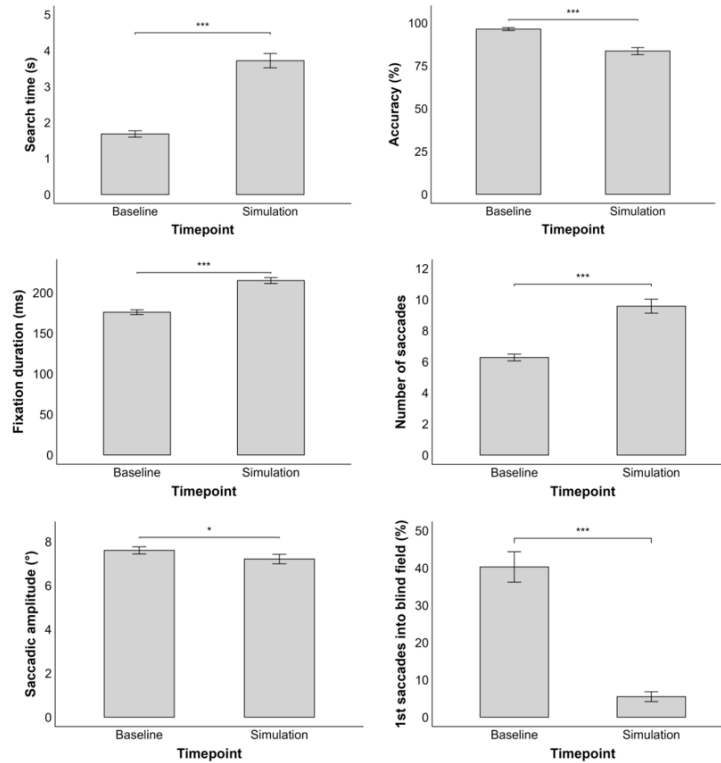
*Comparison of Reading Variables in the Baseline and Simulation Conditions during Silent Reading*



Note. Error bars represent  $\pm 1$  standard error of the mean (SEM). All tests were one-sided. \*\*\* $p < .001$ .

**Figure 10**

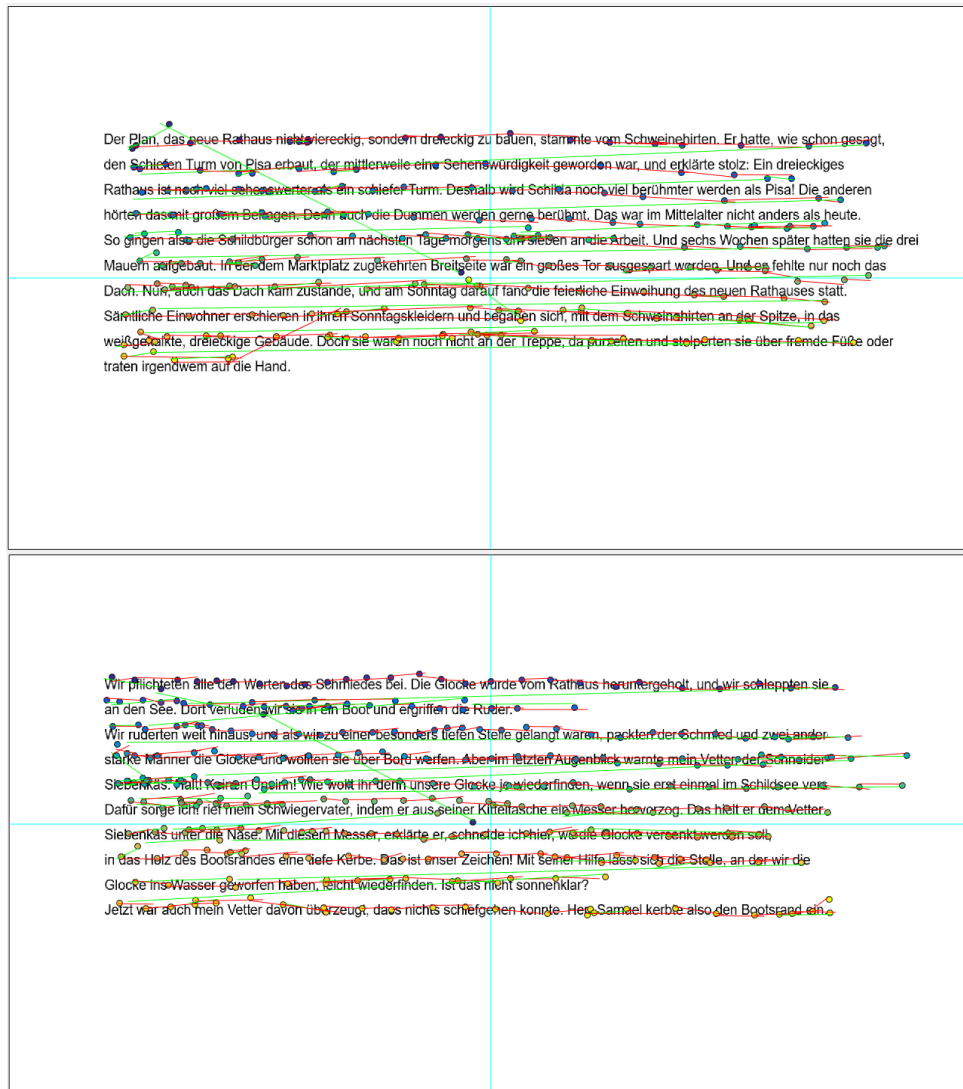
*Comparison of visual search variables in the Baseline and Simulation conditions*



Note. Error bars represent  $\pm 1$  standard error of the mean (SEM). All tests were one-sided. \* $p < .05$ , \*\*\* $p < .001$ .

Figure 11

Eye Movement Patterns in the Baseline and Simulation Conditions during Silent Reading

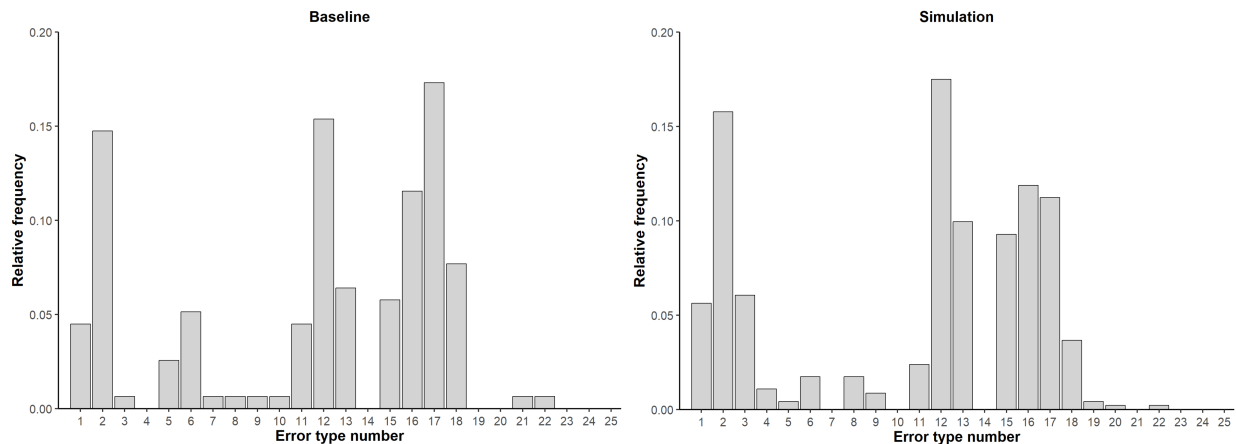


Note. The top panel displays the baseline condition without the hemianopia mask, while the bottom panel shows the pre-training condition with simulated right-sided hemianopia in one of the study participants. Circles represent fixation points, and lines represent saccades. Circle color denotes temporal sequence, where darker colors indicate the beginning of the reading task and lighter colors indicate later points in the task. Red lines represent forward saccades (towards the right), and green lines indicate backward saccades (towards the left).

Another approach to evaluating the effects of the hemianopia simulation was to analyze the types of reading errors made during the reading-aloud task. Descriptive analyses were performed on these errors in both the baseline and simulation conditions. In right-sided hemianopia, we anticipated a higher frequency of reading errors toward the end of words. The total number of reading errors increased nearly threefold under simulated right-sided hemianopia, from 156 at baseline to 463 in the simulation condition (see Appendix, *Table 3*). Despite this increase, the relative frequency distribution of error types showed minimal change across the two time points (see *Figure 12*). At baseline, the most common errors included reordering of letters at the end of words (error type 17), substituting letters in the middle of words (error type 12), and hesitations or pauses within words (error type 2). These error types remained prevalent under simulation, with substitutions in the middle of words and within-word hesitations or pauses again being most frequent. When grouped into five overarching categories, both baseline and simulation conditions showed that most errors occurred at the end of words (error types 15–18), followed by errors affecting reading flow (error types 1–6) and errors in the middle of words (error types 11–14). Errors involving entire words (error types 19–25) or the beginning of words (error types 7–10) were infrequent in both conditions. These findings suggest that while the overall number of reading errors increased under simulated right-sided hemianopia, the distribution of error types remained largely unchanged (see *Figure 13* for a graphical overview).

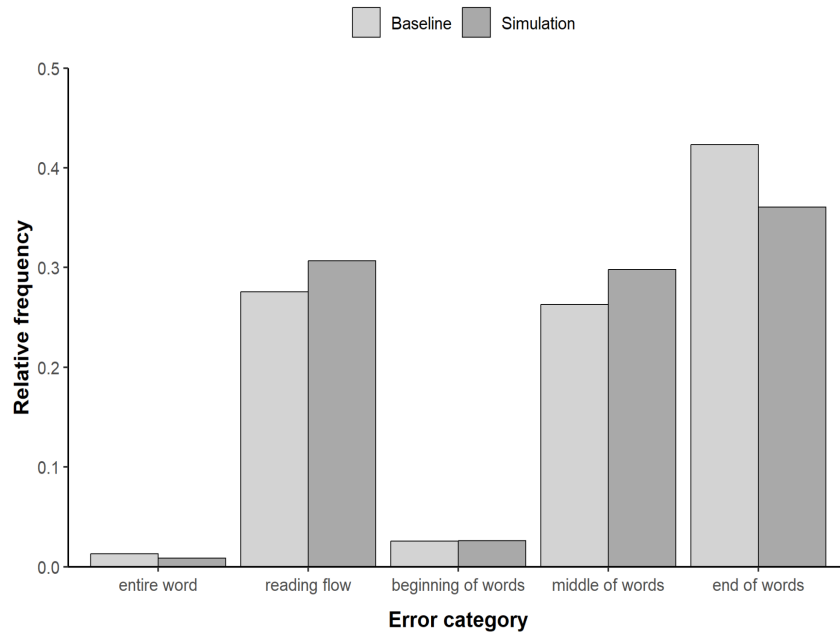
**Figure 12**

*Relative Frequency of Reading Errors in the Baseline and Simulation Conditions*



**Figure 13**

*Relative Frequency of Five Main Reading Error Categories in the Baseline and Simulation Conditions*

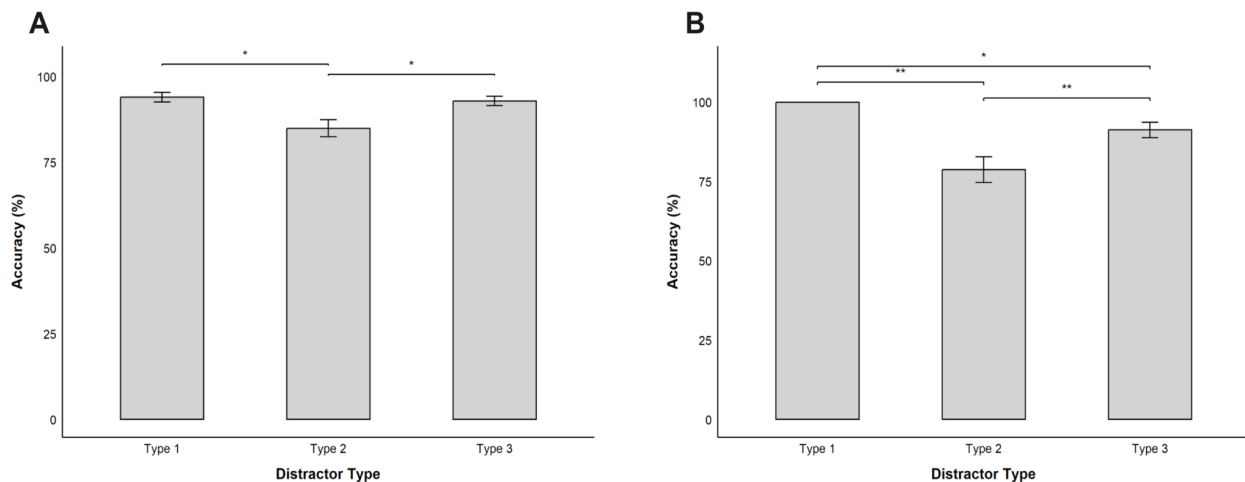


The inclusion of three different distractor types (see *Table 2*) in target-absent trials of parts 1 and 2 of the combination training provided an additional opportunity to assess the impact of the simulation on search time and accuracy. We expected that under right-sided hemianopia simulation, distractor type would influence both search time and accuracy. A Friedman test was conducted to assess differences in performance (accuracy and search time) across target-absent trials with three distractor types (Types 1, 2, and 3) during parts 1 and 2 of the combination training on the first day of training. Results indicated a significant effect of distractor type on accuracy,  $\chi^2(2) = 6.75, p = .03$ . Wilcoxon signed-rank tests with Bonferroni correction revealed that Type 1 ( $M = 94.03\%$ ) yielded significantly higher accuracy than Type 2 ( $M = 84.94\%$ ),  $z = -2.04, p = .02, r = -0.31$  and Type 2 accuracy was lower than Type 3 ( $M = 92.89\%$ ),  $z = -2.25, p = .01, r = -0.34$ . No significant difference was found between Types 1 and 3 ( $p > .05$ ). When analyzing part 2 of the training separately (with fewer but longer pseudo-word stimuli), accuracy differences remained significant,  $\chi^2(2) = 21.44, p < .001$ . Type 1 ( $M = 100\%$ ) showed higher accuracy than both Type 2 ( $M = 78.75\%$ ;  $z = -2.74, p < .01, r = -0.43$ ) and Type 3 ( $M = 91.25\%$ ;  $z = -2.28, p = 0.01, r = -0.36$ ), while Type 2 also showed lower accuracy than Type 3 ( $z = -2.39, p < .01, r = -0.38$ ). Results are illustrated in *Figure 14*.

In terms of search time, distractor type also had a significant effect,  $\chi^2(2) = 29.72, p < .001$ . Type 1 ( $M = 13.85$  s) produced shorter search times than Type 2 ( $M = 15.17$  s;  $z = -2.38, p < .01, r = -0.36$ ) and Type 3 ( $M = 16.78$  s;  $z = -4.82, p < .001, r = -0.73$ ), with Type 2 also resulting in shorter times than Type 3 ( $z = -2.91, p < .01, r = -0.44$ ). For part 2 alone, search times continued to vary significantly by distractor type,  $\chi^2(2) = 30.7, p < .001$ . Type 1 ( $M = 10.49$  s) yielded shorter times than both Type 2 ( $M = 11.67$  s;  $z = -1.79, p = .04, r = -0.28$ ) and Type 3 ( $M = 14.55$  s;  $z = -4.54, p < .001, r = -0.72$ ), with Type 2 also showing shorter times than Type 3 ( $z = -3.77, p < .001, r = -0.57$ ). Results are illustrated in *Figure 15*. Overall, distractor type had a significant impact on both accuracy and search time, with Type 2 leading to the lowest accuracy and Type 3 resulting in the longest search times.

**Figure 14**

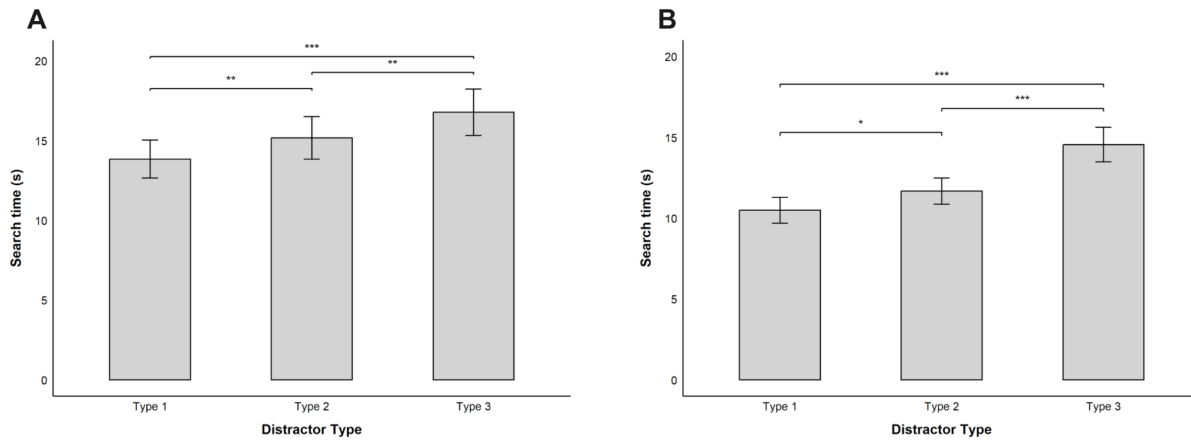
*Percentage of Correct Responses in Target-Absent Trials Across Three Distractor Types in Combination Training*



*Note.* Panel A shows the results for parts 1 and 2 of the first day of combination training, while Panel B shows the results for part 2 only. Distractor Type 1 refers to a pseudo-word formed by changing the beginning of a correct word, Type 2 by changing the middle, and Type 3 by changing the ending. Error bars represent  $\pm 1$  standard error of the mean (SEM). All post-hoc tests were two-sided, except for the comparison between Type 1 and Type 3, which was one-sided. \* $p < .05$ , \*\* $p < .01$ .

**Figure 15**

*Average Search Time in Target-Absent Trials Across Three Distractor Types in Combination Training*



*Note.* Panel A shows the results for parts 1 and 2 of the first day of combination training, while Panel B shows the results for part 2 only. Distractor Type 1 refers to a pseudo-word formed by changing the beginning of a correct word, Type 2 by changing the middle, and Type 3 by changing the ending. Error bars represent  $\pm 1$  standard error of the mean (SEM). All post-hoc tests were two-sided, except for the comparison between Type 1 and Type 3, which was one-sided. \* $p < .05$ , \*\* $p < .01$ . \*\*\* $p < .001$ .

To facilitate interpretation of the results, part 2 of the combination training was evaluated in a sample of 10 healthy participants without simulated hemianopia. Accuracy rates varied slightly by distractor type, with trials involving Type 2 distractors showing a lower average accuracy ( $M = 93.75\%$ ) compared to trials with Type 1 ( $M = 97.50\%$ ) and Type 3 ( $M = 97.50\%$ ) distractors; however, this difference was not statistically significant,  $\chi^2(2, N = 10) = 0.43, p = .81$ . Similarly, average search times showed a small increase for Type 2 distractors ( $M = 7.06$  s) relative to Type 1 ( $M = 6.46$  s) and Type 3 ( $M = 7.02$  s), but this difference was also non-significant,  $\chi^2(2, N = 10) = 4.2, p = .12$ . This confirmed that the significant differences between distractor types described above were attributable to the hemianopia simulation rather than general reading tendencies.

### **Overall training effects**

To assess the effectiveness of training on reading and visual search outcomes, planned comparisons were conducted between the pre-training condition and the average value of each variable of interest across all three post-training conditions, with analyses performed separately for each training group. Largely in line with our hypothesis, the results indicated significant improvements in all assessed variables, except

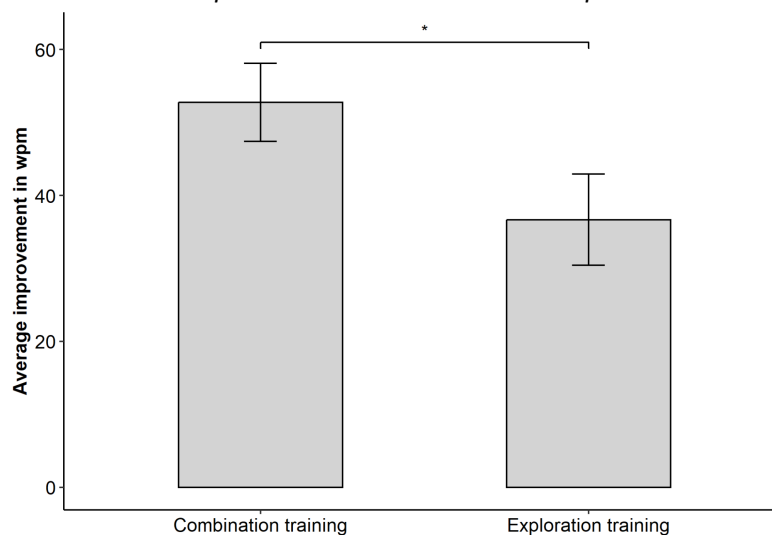
for the number of reading errors while reading aloud in the exploration training group and saccadic amplitude during visual search for both training groups (see Appendix, Table 4). The largest training effects across training groups were found in variables words per minute during reading aloud, with strong effect sizes in both the combination group,  $t(19) = -7.16, p < .001, d = -2.35$ , and the exploration group,  $t(19) = -3.65, p < .001, d = -1.37$ , as well as in reading duration during silent reading, with strong effect sizes in both the combination group,  $t(16) = 4.22, p < .001, d = 0.94$ , and the exploration group,  $t(14) = 4.64, p < .001, d = 1.42$ .

### ***Difference in training effects between the training groups***

To evaluate the effectiveness of training type on reading and visual search outcomes, planned comparisons were conducted between the two training groups, assessing improvements from pre-training to the average performance across all three post-training conditions for each outcome variable. An effect of training type was found for only one outcome variable, namely words per minute. For this variable, the combination training group showed greater improvement than the exploration training group,  $t(37.13) = -1.95, p = .03, d = -0.62$  (see Appendix, Table 5 and Figure 16). All other comparisons revealed no significant differences between the two training groups. Thus, our hypothesis that the combined approach would lead to greater improvements in reading was partially confirmed.

**Figure 16**

*Post-training Improvement in Words per Minute: Combination vs. Exploration Training Groups*



*Note.* Error bars represent  $\pm 1$  standard error of the mean (SEM). \* $p < .05$ .

### Effects of training duration on training-related improvements

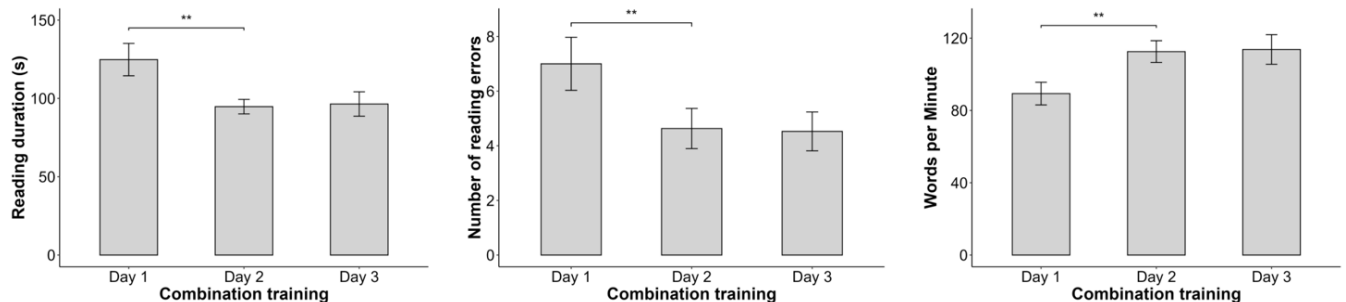
To evaluate the effect of training duration on reading and visual search outcomes, planned comparisons were conducted between post-training assessments on days 1 and 2 as well as days 2 and 3 for each training group and outcome variable, with the FDR correction applied to adjust for multiple comparisons.

For reading outcomes, significant improvements between training days were observed only in the combination training group and only between days 1 and 2 (see Appendix, Table 6). Specifically, participants showed increased reading aloud speed (words per minute:  $t(18) = -3.46, p = .006, d = -0.90$ ), fewer reading errors ( $z = 2.36, p = .018, r = 0.38$ ), and reduced reading duration ( $z = 2.63, p = .012, r = 0.43$ ), indicating improved performance after the second day of training (see Figure 16). No significant differences between training days were found for silent reading (see Appendix, Table 7).

For visual search outcomes, results once again varied by training group and measure. In the combination training group, after adjusting for multiple comparisons, no significant difference in post-training performance was found between the training days (see Appendix, Table 8). In the exploration training group, search time ( $t(19) = 2.36, p = .04, d = 0.41$ ) and the number of saccades until target fixation (i.e., scan path length,  $t(20) = 2.39, p = .04, d = 0.32$ ) decreased further after the second day of training, while fixation duration showed a significant reduction between the second and third days of training ( $t(20) = 3.92, p = .01, d = 0.40$ ). Results are presented in Figure 18. Overall, our hypothesis that extending training would enhance performance improvements was only partially confirmed.

Figure 17

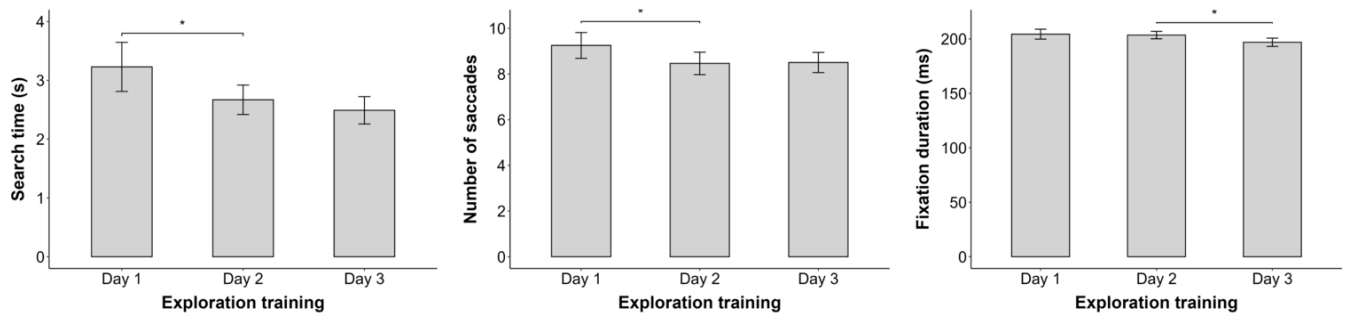
#### Effects of Training Duration on Improvements in Reading Aloud in the Combination Training Group



Note. Error bars represent  $\pm 1$  standard error of the mean (SEM). All tests were one-sided.  $**p < .01$ .

**Figure 18**

*Effects of Training Duration on Improvements in Visual Search in the Exploration Training Group*



Note. Error bars represent  $\pm 1$  standard error of the mean (SEM). All tests were one-sided. \* $p < .05$ .

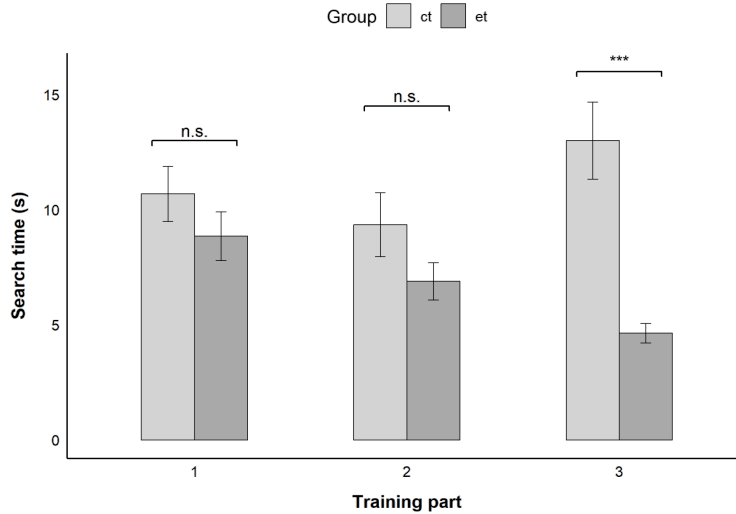
**Results of training data analysis**

*Comparison of performance during combination and exploration training*

To address the question of whether there were differences in difficulty between the two training types, the performance variables search time and accuracy were compared between the two groups for each of the three training parts on the first day of training. Search time was analyzed for trials in which the target stimulus was correctly recognized on the right side. Significant differences between the combination and exploration training groups were found for Part 3 of the first training day ( $z = -5.02$ ,  $p < .001$ ,  $r = -0.78$ ). On average, participants who completed Part 3 of the combination training required significantly more time ( $M = 12.99$  s) to locate the target stimulus on the "blind" side than those in the exploration group ( $M = 4.63$  s), see *Figure 19*. A similar pattern emerged when looking at the search times on the second day of training, with participants completing Part 3 of the combination training requiring more time ( $M = 11.12$ ) to locate the target stimulus than participants completing the exploration training ( $M = 3.56$ ,  $z = -5.66$ ,  $p < .001$ ,  $r = -0.89$ ), see *Figure 20*.

**Figure 19**

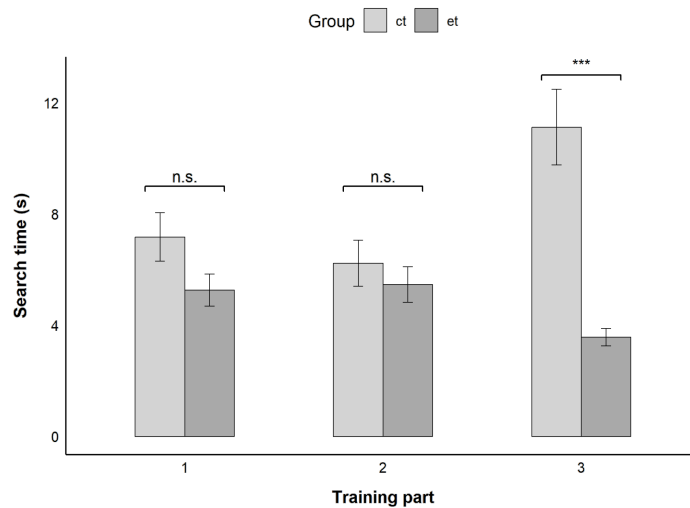
*Average Search Time During the Three Parts of the Combination and Exploration Trainings on the First Day of Training*



*Note.* ct = combination training group; et = exploration training group. Error bars represent  $\pm 1$  standard error of the mean (SEM). Wilcoxon tests were two-sided. n.s. = not significant; \*\*\* $p < .001$ .

**Figure 20**

*Average Search Time During the Three Parts of the Combination and Exploration Trainings on the Second Day of Training*

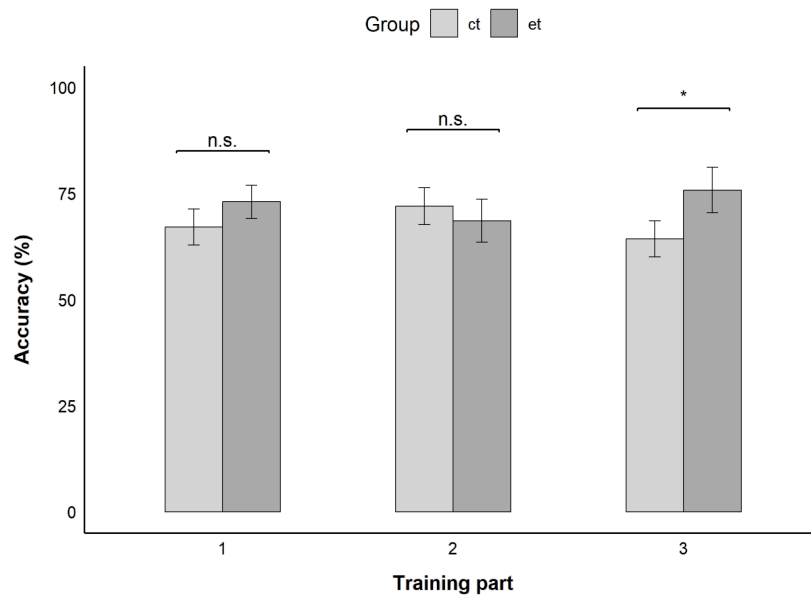


*Note.* ct = combination training group; et = exploration training group. Error bars represent  $\pm 1$  standard error of the mean (SEM). Wilcoxon tests were two-sided. n.s. = not significant; \*\*\* $p < .001$ .

Accuracy was analyzed for trials in which the target stimulus was on the right side. Again, significant differences between the combination and exploration training groups were found for Part 3 of the first training day ( $z = -1.78, p = .04, r = -0.27$ ). On average, participants in the combination training group showed lower accuracy ( $M = 64.28\%$ ) compared to those in the exploration training group ( $M = 75.79\%$ ), as illustrated in *Figure 21*. On the second day of training, the exploration training group showed an increase in average accuracy ( $M = 84.52\%$ ), while the combination training group's accuracy remained steady ( $M = 67.06\%$ ) during the first part of training, resulting in a significant difference between groups ( $z = -2.81, p < .01, r = -0.44$ ). Similar to results from the first day, a significant difference was also observed in Part 3 of the training ( $z = -1.98, p = .02, r = -0.31$ ), with lower accuracy in the combination training group ( $M = 70\%$ ) compared to the exploration training group ( $M = 82.93\%$ ), as shown in *Figure 22*.

**Figure 21**

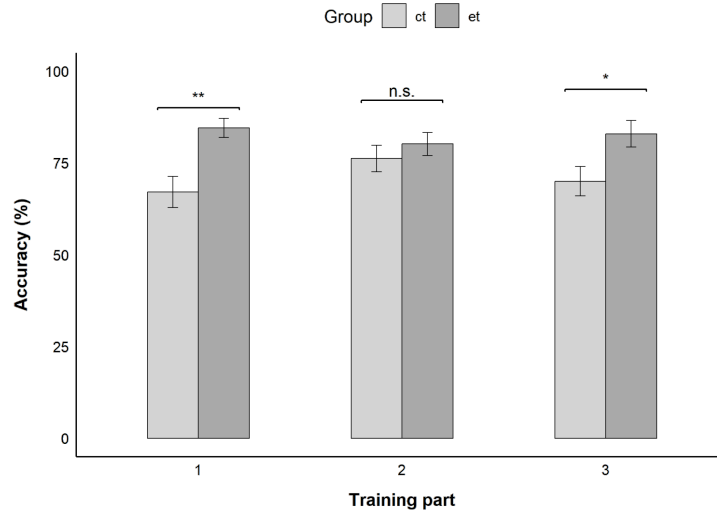
*Average Accuracy During the Three Parts of the Combination and Exploration Trainings on the First Day of Training*



*Note.* *ct* = combination training group; *et* = exploration training group. Error bars represent  $\pm 1$  standard error of the mean (SEM). Wilcoxon tests were two-sided. n.s. = not significant; \* $p < .05$ .

**Figure 22**

*Average Accuracy During the Three Parts of the Combination and Exploration Trainings on Second Day of Training*



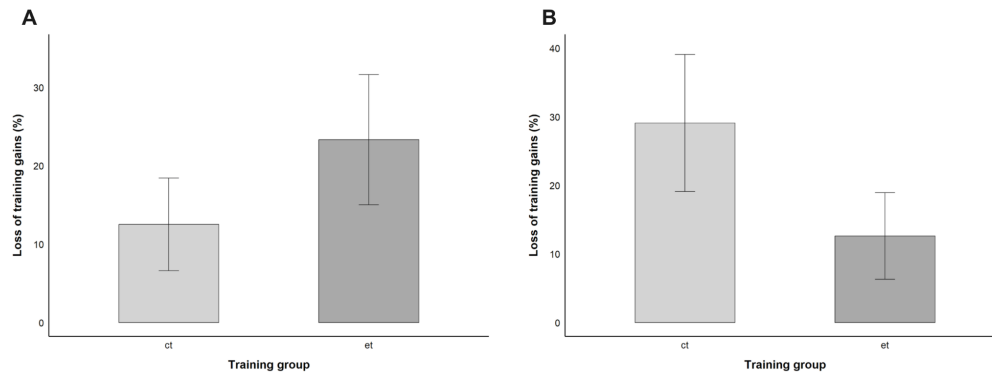
*Note.* *ct* = combination training group; *et* = exploration training group. Error bars represent  $\pm 1$  standard error of the mean (SEM). Wilcoxon tests were two-sided. n.s. = not significant; *ct* = combination training group; *et* = exploration training group. \* $p < 0.05$ , \*\* $p < .01$

*Assessing transfer of training gains to post-training tasks*

Additionally, statistical analysis was conducted on search time data to examine the transfer of training gains to reading duration during loud reading and to search time during the visual search task between the two training groups. The analysis only included participants who demonstrated an improvement in search times during training from the first to the second training day ( $N = 36$ ). The transfer metrics for reading and search times were calculated by subtracting the relative change in reading duration and search time during post-training measurements from the relative decrease in search time during training, respectively. Positive values for these transfer metrics indicated a loss of training gains, while negative values suggested an amplification of gains, with values close to zero indicating retention of gains. Although no significant differences were found between the groups (reading:  $t(34) = -1.0886$ ,  $p = .28$ ; search time:  $z = -.80$ ,  $p = .21$ ), descriptive patterns emerged: the combination training group showed better transfer to reading, retaining more of its training gains compared to the exploration group, while the exploration group demonstrated better transfer to visual search (see *Figure 23*).

**Figure 23**

*Transfer of Training Gains in Search Time to Reading Duration During the Loud Reading Task and to Search Time During the Visual Search Task*



*Note.* Panel A depicts the transfer of training gains to the reading task, while Panel B depicts the transfer of training gains to the visual search task. Smaller values correspond to lower transfer loss. *ct* = combination training group; *et* = exploration training group. Error bars represent  $\pm 1$  standard error of the mean (SEM).

## Discussion

### *Effectiveness of the hemianopia simulation*

In our study, simulating right-sided hemianopia yielded expected outcomes, significantly impairing reading and exploration metrics, notably reducing words per minute and increasing fixation duration and search time during visual tasks. These findings align with documented impairments in hemianopic patients, who typically exhibit prolonged fixation durations and extended reading and search times (Leff & Behrmann, 2008; Machner et al., 2009; Zihl, 1995a, 1999). Our simulation effectively mirrors the reading and search patterns observed in individuals with hemianopia, suggesting that these characteristics are primarily attributable to the hemianopic condition itself, rather than to additional cerebral impairments affecting attentional or sensory processes.

The significantly reduced number of initial saccades into the blind field indicates a lack of spontaneous compensation for the induced visual field deficit. Interestingly, saccadic amplitude during visual search, but not reading, was minimally affected by our simulation, consistent with Pambakian et al. (2000), who reported similar mean saccadic amplitudes between hemianopic patients and controls. This discrepancy raises the question of whether simulating right-sided hemianopia specifically influences saccadic

amplitude differently during reading versus visual search tasks. However, Pambakian et al. (2000) also noted shorter saccades into the blind field compared to the seeing field, a subtle aspect of hemianopia's behavioral pathology that we could not confirm in our study. Biebl et al. (2022) found smaller saccadic amplitudes during driving tasks in left-sided compared to right-sided simulated hemianopia, suggesting task-specific and lateralized effects. Conversely, other studies have reported greater impairments, including smaller saccades, during visual search in right hemianopic patients compared to left (Machner et al., 2009; Hildebrandt et al., 1999). Simpson et al. (2011) highlight a potential reason for the mixed findings regarding changes in saccadic amplitude in real or simulated hemianopia: the neglect of both saccade direction and starting location. They found that saccades toward the blind side had larger amplitudes when originating farther from the blind-side boundary. A key adaptation in visual scanning after hemianopia could therefore be using saccades to direct fixations deeper into the blind side from the seeing side, an effect overlooked without considering direction and starting location together (Simpson et al., 2011).

Analyzing the types of reading errors under baseline and simulated conditions provides additional insight into the effectiveness of the hemianopia simulation. Patients with right-sided hemianopia often fixate to the left of word centers during reading, leading to omissions and guessing errors (Schuett, 2009). Therefore, it was anticipated that simulating right-sided hemianopia would predominantly increase errors at word endings. However, our descriptive analysis revealed that while the simulation increased the total number of errors—nearly tripling compared to baseline—it did not alter the distribution of error types. In both baseline and simulation conditions, errors occurred most frequently at word endings, followed by errors affecting reading flow, and then errors in the middle of words. The rise in total errors under simulated right-sided hemianopia, with no change in error distribution, likely reflects the immediate impact of visual constraints and the lack of compensatory strategies. These findings are challenging to contextualize within the existing literature, as most hemianopia reading studies focus on time-based outcomes rather than reading errors or text comprehension (Tol et al., 2024). This emphasis on reading speed is justified, as Rubin (2013) highlighted its role as a key predictor of vision-related quality of life. However, measures of reading errors and comprehension also hold potential value for understanding reading performance.

An additional analysis of the combination training data examined the influence of distractor types on performance during target-absent trials, measured by accuracy and search time. This analysis also

assessed the effectiveness of the hemianopia simulation, as right-sided hemianopia was expected to impair performance more significantly for distractor type 3, where the word ending was altered. The results showed the lowest accuracy in trials with distractor type 2, where words were altered in the middle. This finding aligns with the “typoglycemia” phenomenon, which highlights that readers rely heavily on the beginning and ending of words, allowing the brain to infer the middle—making mid-word changes harder to detect (Rayner et al., 2006). Accuracy differences between distractor types 1 (beginning changed) and 3 (ending changed) were minimal when parts 1 and 2 of training were combined, likely because part 1 used shorter words that fit within the simulated macular sparing window. However, in part 2, where words were longer, accuracy dropped significantly for distractor type 3 compared to type 1, as these changes extended beyond the sparing zone. Search times mirrored these findings, with longer times for distractors altered further from the word beginning (type 3 > type 2 > type 1). This pattern remained consistent across all training parts, demonstrating expected hemianopic deficits. To confirm these effects were specific to the hemianopia simulation, additional data were collected from a healthy sample without the simulation mask. These control data revealed no similar differences in accuracy or search times, verifying that the observed impairments were unique to the simulated hemianopia. These results validate the simulation's effectiveness in replicating deficits characteristic of real hemianopia. A significant advantage of simulating hemianopia in healthy participants is the ability to quantify pre-morbid performance at baseline, typically unknown in hemianopic patients, allowing for intrapersonal comparisons. Simulating hemianopia in healthy participants also offers a unique opportunity to investigate the immediate effects of visual field loss and separate it from the effects of possible comorbidities, a scenario that is challenging to study in actual hemianopic patients.

### ***Effectiveness of the interventions***

The findings from this study revealed significant improvements across the majority of reading and exploration outcome measures in both the combination and exploration training groups, underscoring the overall effectiveness of the interventions. However, two exceptions were noted: reading errors in the exploration training group and saccadic amplitude during visual search in both groups showed no improvement. The lack of change in saccadic amplitude during visual search may be attributed to a ceiling effect, as the amplitudes under simulated hemianopia were already close to baseline (healthy) levels prior to training. This suggests limited room for further enhancement through training. In the case of reading errors in the exploration training group, the absence of a reading-specific component likely explains the stagnation. Unlike participants in the combination training group, those in the exploration group did not

practice reading tasks directly, which may have constrained their ability to improve reading accuracy. Nonetheless, exploration training did yield gains in reading speed, contributing to a significant improvement in words per minute, a composite measure of both speed and accuracy. At the same time, words per minute was the only outcome variable where the combination group showed significantly greater improvement compared to the exploration group. This underscores the specific strengths of each approach while highlighting the added value of integrating reading and exploration components for more comprehensive rehabilitation.

The benefits of combination training may even be underestimated in this study, as it was compared to a fairly specific form of exploration training, which, while devoid of explicit word stimuli, still included graphical elements sharing aspects with strings of symbols and therefore may have triggered some cognitive processes that are also relevant for reading. Combination training could also offer more substantial benefits for hemianopic patients, as the compensatory strategies acquired during training can be directly applied and reinforced in daily life. Unlike simulated hemianopia, where participants experience impairments and learn compensatory strategies only during sessions, hemianopic patients suffer from the same deficits inside and outside of the lab and can therefore apply the techniques learned during therapy also to all other situations, thereby continuously utilizing and refining these techniques, leading to more effective rehabilitation.

The greater overall improvements observed in the combination training compared to exploration training raise the question of whether this advantage is primarily due to the presence of linguistic stimuli or if other factors contribute to its effectiveness. One possibility is that combination training is inherently more demanding, leading to greater training gains. A comparison of training difficulty between the two methods found no significant differences in performance during the first two parts of the trainings. However, in part three, combination training was more challenging, as indicated by longer search times and lower accuracy. This increased difficulty likely resulted from the complexity of the sentence-based stimuli, which required greater cognitive and oculomotor engagement. In contrast, the stimuli in the exploration training may have been more easily segmented. Their length or density could have made the defining feature within the target stimulus more salient, transforming what might otherwise be a serial search into a more efficient "pop-out" search. While the greater difficulty of combination training may have contributed to more robust learning, it does not fully explain the results, as its benefits were most pronounced in reading-related variables. Thus, the combination of linguistic components and increased task difficulty likely played a role in its superior outcomes.

Further comparison between combination and exploration training revealed distinct patterns of skill transfer to post-training tasks. Descriptively, combination training group retained more of its search time gains in the reading task, and exploration training group retained more of its search time gains in the visual search task. These patterns highlight the distinct strengths of each training type: combination training offers particular advantages for reading-related tasks, while exploration training enhances broader perceptual skills. Further support for task-specific components driving improvements in related performance areas comes from the analysis of the effects of training duration. In the combination training group, reading aloud metrics—words per minute, reading accuracy, and reading duration—showed significant gains from day one to day two. Similarly, the exploration group exhibited further enhancements in visual search parameters: search time and number of saccades improved after the second day, and fixation duration after the third day of training. Collectively, these findings underscore the potential utility of tailored training approaches depending on the desired transfer outcome. Nonetheless, as combination training improved both reading and visual search outcomes in this study, combined approaches may offer a comprehensive solution for addressing multiple functional needs.

Although some outcome measures showed task-specific improvements with longer training durations, most measures reached a plateau after the first training day. This plateau may be attributed to the healthy participant sample, who likely experienced rapid initial improvements that stabilized quickly. Alternatively, the training may not have been long enough to trigger further improvements, as gains often accumulate gradually over hundreds of trials (Sireteanu & Rettenbach, 1995, 2000; Leonards et al., 2002). Additionally, the lack of opportunities for participants to practice the learned eye movement patterns outside the laboratory setting may have limited further progress. In contrast to hemianopic patients, who can apply compensatory strategies in daily life, healthy participants revert to normal visual experiences after each session, potentially hindering the consolidation of training effects. These findings are consistent with previous research on simulated hemianopia (Schuett et al., 2009a, 2009b; Simpson et al., 2011) suggesting that while initial training can produce significant improvements, the absence of real-world application may restrict long-term retention and further skill enhancement. Furthermore, the findings highlight both the potential and limitations of simulated hemianopia in understanding and treating the condition. While simulation studies may offer valuable insights into behavioral adaptations and the overall effectiveness of training techniques, they fall short in capturing the long-term mechanisms that drive sustained improvements in hemianopia.

## ***Limitations***

While the present study demonstrates valuable insights into training outcomes for simulated hemianopia, several limitations should be considered. First, spontaneous compensation strategies were not directly addressed in this study. While patients with hemianopia do not consistently develop such strategies (McDonald et al., 2006), healthy participants with simulated hemianopia can do so relatively easily, as shown in prior research (Schuett et al., 2009a, 2009b). Consequently, it remains unclear whether the observed improvements in outcome variables were primarily the result of the training itself or whether spontaneously adopted compensatory behaviors also played a role.

The exploration training in this study included elements resembling reading tasks, though without the lexical-semantic and directional demands of actual reading. These similarities may have reduced the relative advantage of combination training and contributed to the positive effects of exploration training on most of the reading outcomes. This complicates comparisons with studies using conventional visual search training, such as Vialatte et al. (2023), who found that symbol-based visual search training enhanced reading in dyslexic children. However, our findings align with Schuett et al. (2008a), who demonstrated that reading training does not necessarily require text-based stimuli. Their study showed that training with word-like digit sequences, which promoted similar saccadic patterns, was just as effective as conventional text training in improving reading performance and associated eye movements.

Another limitation lies in the use of simulated hemianopia. While our simulation effectively approximates real hemianopic deficits, it does not account for the heterogeneity of comorbid conditions or variability in the size, location, and extent of damage to the visual pathways that are common in actual patients. Real hemianopia patients often experience additional challenges, such as attentional and cognitive impairments, that may affect training outcomes. Testing the combination training in real hemianopia populations is necessary to determine whether the observed improvements in both reading and visual search tasks can be replicated under more complex clinical conditions, where spontaneous compensation strategies might also be less prevalent.

Finally, the age of the participants in this study (mean age = 25.45 years) further limits the generalizability of findings to real hemianopia populations, which predominantly consist of individuals over 50 years old (Fujino et al., 1986; Kedar et al., 2006; Smith, 1962). Age-related cognitive changes and functional limitations may influence the effectiveness of compensatory training. While some studies suggest that age impacts rehabilitation success (Tant et al., 2002), others report only marginal effects (Zihl et al., 2021).

Further research is needed to clarify the role of age in training outcomes for hemianopia rehabilitation. These limitations highlight the need for future studies to investigate compensatory strategies and the applicability of these findings to real hemianopia populations across varying age groups.

### ***Conclusion***

The combination training in this study showed promising improvements in both reading and exploration performance under simulated right-sided hemianopia. While exploration training also had positive effects, a unified training paradigm targeting both skills may provide a more effective approach to compensatory therapy. Interestingly, performance gains plateaued after the first day, suggesting limited benefit from extended training. Future research should compare combination training with conventional exploration and reading-specific training to clarify its relative efficacy. Long-term stability of improvements and applicability to actual hemianopia (both right-sided and left-sided) also warrant investigation. This will determine whether combination training can be effectively integrated into rehabilitation practices.

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## Appendix

**Table 1**

*Error Types in the Analysis of the Reading Aloud-Task*

Number	Category	Error type
1.	Reading flow	Hesitations/pauses at the beginning of words
2.		Hesitations/pauses within words
3.		Breaking up of words into individual letters
4.		Breaking up of words into segments (syllabic reading)
5.		Skipping punctuation marks
6.		Losing track of the line
7.	Beginning of words	Omissions at the beginning of words
8.		Substitution of letters at the beginning of words
9.		Reordering of letters at the beginning of words
10.		Additions at the beginning of words
11.	Middle of words	Omissions in the middle of words
12.		Substitution of letters in the middle of words
13.		Reordering of letters in the middle of words
14.		Additions in the middle of words
15.	End of words	Omissions at the end of words
16.		Substitution of letters at the end of words
17.		Reordering of letters at the end of words
18.		Additions at the end of words
19.	Entire word	Omissions of entire words/larger word components
20.		Alteration of entire words/larger word components
21.		Additions of entire words/larger word components
22.		Formation of "word ruins" into real words
23.		Formation of "word ruins" into pseudowords
24.		Partially recognized letters incorrectly ordered to form a word
25.		Reordering of words or larger word components

**Table 2**

*Comparison between the Baseline and the Simulation Measurements (Pre-Training) for all Reading and Visual Search Outcomes*

<b>Task</b>	<b>Outcome Variable</b>	<b>Test</b>	<b>Statistic</b>	<b>Effect Size</b>
<b>Reading aloud</b>	<i>Reading Duration</i>	Wilcoxon-Test	$z = -5.50^{***}$	$r = .61$
	<i>Number of Errors</i>	Wilcoxon-Test	$z = -5.18^{***}$	$r = .58$
	<i>Words per Minute</i>	t-test	$t(39) = 18.36^{***}$	$d = 4.37$
<b>Silent reading</b>	<i>Reading Duration</i>	Wilcoxon-Test	$z = -5.51^{***}$	$r = .61$
	<i>Number of Fixations</i>	Wilcoxon-Test	$z = -5.57^{***}$	$r = .61$
	<i>Fixation Duration</i>	t-test	$t(40) = -11.28^{***}$	$d = 1.76$
	<i>Saccadic Amplitude</i>	t-test	$t(40) = 9.15^{***}$	$d = 1.43$
	<i>Number of Regressions</i>	Wilcoxon-Test	$z = -4.71^{***}$	$r = .52$
<b>Visual search</b>	<i>Search Time</i>	t-test	$t(38) = -11.66^{***}$	$d = 1.87$
	<i>Accuracy</i>	Wilcoxon-Test	$z = -4.56^{***}$	$r = .52$
	<i>Fixation Duration</i>	t-test	$t(39) = -19.91^{***}$	$d = 3.15$
	<i>Number of Saccades</i>	t-test	$t(39) = -8.67^{***}$	$d = 1.37$
	<i>Saccadic Amplitude</i>	t-test	$t(39) = 2.20^*$	$d = .35$
	<i>Percentage of First Saccades into Blind Field</i>	t-test	$t(39) = 8.23^{***}$	$d = 1.30$

*Note.* The Wilcoxon-Test was used for non-parametric comparisons, and the t-test was used for parametric comparisons. All tests were one-tailed and significance was set at  $p < .05$ . Effect sizes are reported as  $r$  for Wilcoxon tests and Cohen's  $d$  for t-test. \*  $p < .05$ . \*\*\*  $p < .001$ .

**Table 3***Absolute Frequency of reading Errors in the Total Sample: Baseline and Simulation Measurements*

Number	Error type	Baseline	Simulation
1.	Hesitations/pauses at the beginning of words	7	26
2.	Hesitations/pauses within words	23	73
3.	Breaking up of words into individual letters	1	28
4.	Breaking up of words into segments (syllabic reading)	0	5
5.	Skipping punctuation marks	4	2
6.	Losing track of the line	8	8
7.	Omissions at the beginning of words	1	0
8.	Substitution of letters at the beginning of words	1	8
9.	Reordering of letters at the beginning of words	1	4
10.	Additions at the beginning of words	1	0
11.	Omissions in the middle of words	7	11
12.	Substitution of letters in the middle of words	24	81
13.	Reordering of letters in the middle of words	10	46
14.	Additions in the middle of words	0	0
15.	Omissions at the end of words	9	43
16.	Substitution of letters at the end of words	18	55
17.	Reordering of letters at the end of words	27	52
18.	Additions at the end of words	12	17
19.	Omissions of entire words/larger word components	0	2
20.	Alteration of entire words/larger word components	0	1
21.	Additions of entire words/larger word components	1	0
22.	Formation of "word ruins" into real words	1	1
23.	Formation of "word ruins" into pseudowords	0	0
24.	Partially recognized letters incorrectly ordered to form a word	0	0
25.	Reordering of words or larger word components	0	0
<b>Total</b>		<b>156</b>	<b>463</b>

**Table 4***The Effects of Training on Reading and Visual Search Outcomes*

Task	Outcome Variable	Combination Training		Exploration Training	
		Statistic	Effect size	Statistic	Effect size
Reading aloud	<i>Reading Duration</i>	z = 4.42***	r = 0.70	z = 2.91**	r = 0.46
	<i>Number of Errors</i>	z = 2.75**	r = 0.42	z = 1.17	-
	<i>Words per Minute</i>	t(19) = -7.16***	d = -2.35	t(19) = -3.65***	d = -1.37
Silent reading	<i>Reading Duration</i>	t(16) = 4.22***	d = 0.94	t(14) = 4.64***	d = 1.42
	<i>Number of Fixations</i>	t(19) = 4.89***	d = 1.13	t(19) = 5.49***	d = 0.95
	<i>Fixation Duration</i>	t(19) = 5.33***	d = 0.63	t(20) = 3.79***	d = 0.94
	<i>Saccadic Amplitude</i>	z = 2.51**	r = 0.40	t(19) = -3.34**	d = -0.66
	<i>Number of Regressions</i>	z = 2.26*	r = 0.25	t(19) = 2.14*	d = 0.52
Visual search	<i>Search Time</i>	t(18) = 3.59**	d = 0.96	t(19) = 3.76***	d = 0.97
	<i>Accuracy</i>	z = -2.79**	r = -0.45	z = -2.66**	r = -0.41
	<i>Fixation Duration</i>	t(18) = 4.19***	d = 0.59	t(20) = 3.26**	d = 0.58
	<i>Number of Saccades</i>	t(18) = 2.05*	d = 0.53	t(20) = 1.79*	d = 0.36
	<i>Saccadic Amplitude</i>	t(20) = 0.95	-	t(18) = -1.1	-
	<i>Percentage of First Saccades into Blind Field</i>	z = -2.44**	r = -0.39	z = -3.44***	r = -0.53

*Note.* Comparisons between the pre-training condition and the average value of each variable of interest across all three post-training conditions. The Wilcoxon-Test was used for non-parametric comparisons, and the t-test was used for parametric comparisons. All tests were one-tailed and significance was set at  $p < .05$ . Effect sizes are reported as  $r$  for Wilcoxon tests and Cohen's  $d$  for t-test. \*  $p < .05$ . \*\*  $p < .01$ . \*\*\*  $p < .001$ .

**Table 5**

*Difference Between the Combination and Exploration Trainings in their Effects on Reading and Visual Search Outcomes*

<b>Task</b>	<b>Outcome Variable</b>	<b>Test</b>	<b>Statistic</b>	<b>Effect Size</b>
<b>Reading aloud</b>	<i>Reading Duration</i>	Wilcoxon-Test	$z = 0.57$	-
	<i>Number of Errors</i>	t-test	$t(37.99) = 1.25$	-
	<i>Words per Minute</i>	t-test	$t(37.13) = -1.95^*$	$d = -0.62$
<b>Silent reading</b>	<i>Reading Duration</i>	t-test	$t(29.39) = -0.53$	-
	<i>Number of Fixations</i>	t-test	$t(37.76) = -0.13$	-
	<i>Fixation Duration</i>	t-test	$t(33.98) = -0.28$	-
	<i>Saccadic Amplitude</i>	t-test	$t(35.13) = -0.32$	-
	<i>Number of Regressions</i>	t-test	$t(37.52) = 0.70$	-
<b>Visual search</b>	<i>Search Time</i>	t-test	$t(36.37) = 0.15$	-
	<i>Accuracy</i>	t-test	$t(37.96) = -0.18$	-
	<i>Fixation Duration</i>	t-test	$t(37.98) = 0.47$	-
	<i>Number of Saccades</i>	t-test	$t(37.84) = 0.19$	-
	<i>Saccadic Amplitude</i>	t-test	$t(32.46) = -1.44$	-
	<i>Percentage of First Saccades into Blind Field</i>	t-test	$t(36.83) = 0.89$	-

*Note.* The Wilcoxon-Test was used for non-parametric comparisons, and the t-test was used for parametric comparisons. All tests for the reading task were one-tailed, while the tests for the visual search variables were two-tailed. Significance was set at  $p < .05$ . Effect size is reported as Cohen's  $d$  for t-test. \*  $p < .05$ .

**Table 6***Effects of Training Duration on Reading Aloud Variables for Each Training Group*

Variable	Combination Training		Exploration Training	
	Post1-Post2	Post2-Post3	Post1-Post2	Post2-Post3
<b>Words per Minute</b>	t(18) = -3.46, p = .006**, d = -0.90	t(18) = -0.55, p = .43	t(16) = -0.04, p = 0.85	t(16) = 0.94, p = .85
<b>Number of Errors</b>	Wilcoxon-Test (z = 2.36, p = .018*, r = 0.38)	t(18) = 0.13, p = .54	t(16) = 1.12, p = .84	t(16) = -1.08, p = .85
<b>Reading Duration</b>	Wilcoxon-Test (z = 2.63, p = .012*, r = 0.43)	Wilcoxon-Test (z = 0.54, p = .54)	Wilcoxon-Test (z = -0.09, p = .85)	Wilcoxon-Test (z = -0.92, p = .85)

*Note.* The Wilcoxon-Test was used for non-parametric comparisons, and the t-test was used for parametric comparisons. All tests were one-tailed. False Discovery Rate (FDR) correction was applied to correct for multiple comparisons. Effect size is reported as Cohen's d for t-test. \* p<.05. \*\* p<.01.

**Table 7***Effects of Training Duration on Silent Reading Variables for Each Training Group*

Variable	Combination Training		Exploration Training	
	Post1-Post2	Post2-Post3	Post1-Post2	Post2-Post3
<b>Reading Duration</b>	t(19) = 0.59, p = .46	t(17) = 1.06, p = .46	t(16) = 1.67, p = .30	t(16) = 1.01, p = .43
<b>Number of Fixations</b>	t(20) = -0.29, p = .67	t(20) = 0.45, p = .46	t(18) = 0.82, p = .43	t(18) = 0.59, p = .43
<b>Fixation Duration</b>	t(20) = 1.05, p = .46	t(20) = 0.54, p = .46	Wilcoxon-Test (z = 0.57, p = .43)	t(19) = 0.39, p = .43
<b>Saccadic Amplitude</b>	t(20) = -1.32, p = .46	t(20) = 0.47, p = .68	t(18) = -0.26, p = .43	t(18) = 0.44, p = .67
<b>Number of Regressions</b>	Wilcoxon-Test (z = 0.45, p = .46)	t(20) = 0.28, p = .49	t(18) = 1.75, p = .30	Wilcoxon-Test (z = 0.35, p = .43)

*Note.* The Wilcoxon-Test was used for non-parametric comparisons, and the t-test was used for parametric comparisons. All tests were one-tailed. False Discovery Rate (FDR) correction was applied to correct for multiple comparisons.

**Table 8***Effects of Training Duration on Visual Search Variables for Each Training Group*

Variable	Combination Training		Exploration Training	
	Post1-Post2	Post2-Post3	Post1-Post2	Post2-Post3
<b>Search Time</b>	t(20) = 0.78, p = .42	t(20) = 0.43, p = .42	t(19) = 2.36, p = <b>.04*</b> , d = 0.41	Wilcoxon-Test (z = 1.58, p = .15)
<b>Accuracy</b>	t(20) = -0.35, p = .42	t(20) = -0.69, p = .42	Wilcoxon-Test (z = -0.59, p = .46)	t(20) < 0.001, p = .60
<b>Fixation Duration</b>	t(20) = 2.46, p = .06,	t(20) = 0.45, p = .42	t(20) = .34, p = .49	t(20) = 3.92, p = <b>.01*</b> , d = 0.40
<b>Number of Saccades</b>	t(20) = 0.49, p = .42	t(20) = 0.28, p = .42	t(20) = 2.39, p = <b>.04*</b> , d = 0.32	t(20) = -0.13, p = .60
<b>Saccadic Amplitude</b>	t(20) = -2.39, p = .06	t(20) = -1.58, p = .24)	t(20) = -1.51, p = .17	t(20) = -0.42, p = .49
<b>Percentage of First Saccades into Blind Field</b>	Wilcoxon-Test (z = -0.07, p = .47)	t(20) = -0.74, p = .42	t(20) = -1.26, p = .22	t(20) = 0.30, p = 1.0

*Note.* The Wilcoxon-Test was used for non-parametric comparisons, and the t-test was used for parametric comparisons. All tests were one-tailed. False Discovery Rate (FDR) correction was applied to correct for multiple comparisons. Effect size is reported as Cohen's d for t-test. \* p<.05

### 3. General Discussion

In the present dissertation, we sought to advance standard compensatory rehabilitation approaches for individuals with HVFDs by addressing two persistent limitations: their confinement to static, screen-based environments that primarily target eye movements while neglecting the role of head movements in visual exploration, and their task-specificity, which often limits the transfer of training effects to other functionally relevant domains. To tackle these challenges, we conducted two complementary studies. The first study evaluated the feasibility and efficacy of a home-based VR visual search training program for individuals with HVFDs. By leveraging the immersive capabilities of VR, we enabled participants to train exploration within a substantially larger visual field. Over a 12-week period, participants progressed through three training phases: a placebo phase, an eye movement training phase, and a head movement training phase. The results demonstrated the feasibility and high acceptability of VR-based rehabilitation, with strong adherence rates and rather minimal technical issues. Critically, the combined effects of the two active training phases led to significant improvements in visual search performance, evidenced by reductions in search time and number of saccades, alongside a trend toward increased orientation of initial saccades into the blind field. These findings underscore VR's potential as a promising and effective tool for visual rehabilitation. In the second study, we addressed the issue of task-specificity by developing a novel integrated training paradigm that simultaneously targeted visual exploration and reading. Using a simulated hemianopia model in healthy participants, we compared the efficacy of this combined training with a visual exploration training lacking text-based stimuli. While both approaches produced significant improvements in visual exploration and reading outcomes, greater gains in reading performance were observed after combined training, highlighting the added value of incorporating text-based components to visual exploration training. In the following sections, we reflect on the clinical relevance of these findings and contextualize them within the broader literature, delineate methodological considerations that arose during the studies, and discuss challenges associated with designing ecologically valid, transferable compensatory interventions. Finally, we reflect on the implications of our results for future directions in visual rehabilitation.

#### *3.1. What the trainings revealed: An evaluation of outcomes*

With the first study, we aimed to evaluate the impact of three distinct training phases within a VR-based visual search training program, focusing primarily on changes in performance and oculomotor behavior during visual search tasks. The principal metric for assessing visual search efficiency was search time, while

secondary indicators included various oculomotor parameters. Although it was initially hypothesized that the eye movement training phase (EMT) would produce superior outcomes compared to placebo, this expectation was not supported by the results. We also investigated whether adding a head movement training phase (HMT) would provide additional benefits beyond EMT alone; however, this was not supported by the findings. Notably, the combination of EMT and HMT yielded significant improvements relative to placebo, including quicker search times, fewer saccades, and a tendency for more first saccades to be directed toward the blind field. Contrary to Zihl's (1995a) suggestion that head movements might impair visual scanning, the inclusion of HMT did not detract from improvements after EMT. This approach conceptually aligns with the InSight-Hemianopia Compensatory Scanning Training (IH-CST) developed by de Haan and colleagues (2015b), which also adopted a stepwise training model that prioritizes eye movements first and then head movements to enhance scanning strategies and peripheral target detection during navigational tasks.

As articulated in the introduction of this dissertation, the central aim of our work was to contribute to the development of rehabilitation interventions for individuals with HVFDs that are clinically meaningful, widely accessible and well-aligned with the practical demands of everyday life. Reflecting on the outcomes of our home-based VR visual search training program, we can now evaluate how effectively we met our objectives in terms of clinical relevance, which includes real-world applicability, and overall accessibility.

The clinical utility of our intervention is supported by the observed improvements in visual search efficiency when EMT was combined with HMT. While EMT alone did not significantly outperform the placebo condition, its integration with HMT yielded statistically and clinically meaningful benefits. This underscores the value of a holistic rehabilitative approach that includes both eye and head movement strategies. Specifically, participants demonstrated faster search times and fewer saccades—indicators of more efficient visual search behavior—which are translatable to essential daily activities such as navigation, object localization, and hazard detection. The observed trend toward more first saccades into the blind field also suggests enhanced compensatory behavior. Improved search time often entails a trade-off in accuracy (Hu et al., 2024). Notably, in our study, the reduction in search time did not come at the cost of accuracy. This strengthens the clinical relevance of our results, given that balancing speed and precision is essential for optimal real-world functioning.

Although our study did not directly assess the intervention's impact on ADLs, prior literature supports the generalizability of laboratory-based visual search performance to naturalistic settings. Ramzaou and

colleagues (2018) argue that static, screen-based visual search tasks capture the same underlying cognitive-perceptual mechanisms involved in real-world search behaviors. For example, research during search of everyday objects in healthy individuals revealed systematic patterns that align with those from traditional screen-based studies, such as first fixations being influenced by salient or expected features (Foulsham et al., 2014). Similarly, Botch and colleagues (2023) demonstrated a strong correspondence between classic computer-based and naturalistic, VR-based search tasks. Despite differences in complexity and movement (only eye movements in the computer-based visual search task vs. head and eye movements in a naturalistic search task), participants' search performance was affected by the number of items in the visual display in both types of tasks. Moreover, individual differences in search efficiency in the lab reliably predicted performance in naturalistic, VR-based tasks. These findings provide a theoretical foundation for extending our observed training effects to practical scenarios. Based on existing literature, it is reasonable to infer that the enhanced visual search efficiency observed in our study may translate to improved functional performance in daily life, though further direct investigation would be valuable.

A further strength of our VR-based intervention lies in its alignment with the motor demands of real-world visual exploration. By incorporating head movement training, we moved beyond isolated oculomotor strategies and simulated a more ecologically valid search experience. This allowed participants to engage a larger portion of their visual field and practice compensatory strategies more reflective of real-world behavior. While the training tasks employed simple two-dimensional stimuli rather than complex, context-rich environments (e.g., simulated supermarket searches as seen in Dehn et al., 2020), this choice was a deliberate trade-off to mitigate the risk of cybersickness or seizure induction in our neurologically vulnerable population. Despite this simplification, the intervention yielded improvements in both primary and secondary outcome measures, suggesting that even basic stimuli can effectively train foundational visual search skills when presented in a structured and engaging VR format.

In terms of accessibility, our intervention demonstrates encouraging potential, though several limitations remain. Economically, the study originally employed relatively low-cost VR devices such as Google Daydream and Oculus Go, which provided adequate immersive experiences at prices accessible to most patients (approximately €30 and €200, respectively). While these specific models have since been discontinued, comparable alternatives remain on the market, such as budget-friendly smartphone-based headsets and relatively affordable standalone options like the Meta Quest 3S, currently priced at around

€300. Thus, economic accessibility is still feasible, albeit with considerations for device updates and long-term sustainability.

Physically, the training setup was inclusive of individuals with mild to moderate motor impairments. Participants were able to engage in the training while seated, using only one hand to control the device. Headsets were lightweight and compatible with glasses, though issues such as the loosening of straps and lack of lens adjustability occasionally interfered with comfort and visual clarity. Cognitively, the application was user-friendly, offering simple instructions, intuitive navigation, and both trial-based and session-based feedback, which supported user understanding and motivation. However, reliance on written instructions may pose a barrier for individuals with reading difficulties—an issue that could be addressed by incorporating audio or image-based guidance in future iterations. The training's technical accessibility was more constrained; installation of the app required the experimenter's involvement and was not plug-and-play, limiting complete autonomy. Nevertheless, once installed, the application required minimal technical maintenance and functioned reliably on the selected hardware. Overall, while some aspects of the intervention, particularly the initial technical setup, require support, the core training tasks were accessible across a broad range of economic, physical, and cognitive capabilities, supporting the feasibility of home-based implementation with minimal supervision after setup.

In conclusion, the findings of this study largely support the clinical relevance and accessibility of our home-based VR visual search training program. Clinically, the combination of eye and head movement training produced significant gains in visual search efficiency, with theoretical and empirical evidence suggesting transferability to real-world activities. While certain practical barriers in technical setup and long-term device support remain to be addressed, the training was economically viable, physically inclusive, and cognitively approachable for most patients. Finally, by incorporating head movements and supporting wide-field exploration, our intervention was aligned with the visual demands of everyday life, even in the absence of high-complexity environmental simulations.

In the second study, we demonstrated that in simulated right-sided hemianopia, incorporating text-based stimuli into visual exploration training not only improved visual search comparably to training without text-based elements but also led to greater gains in reading performance. The greater reading improvements observed with the combined training underscore task-specific learning in neurorehabilitation (Schuett et al., 2012; Zihl et al, 2021). Training that incorporates task-relevant stimuli

(e.g., text for reading) appears to foster more targeted and transferable skill acquisition compared to broader, non-specific exploration training.

These findings have important clinical implications for the rehabilitation of individuals with hemianopia, which affects not only visual exploration but also reading abilities, particularly in patients with right-sided visual field deficits (Goodwin et al., 2014; Leff et al., 2000; Trauzettel-Klosinski, 2002). A training program that simultaneously targets both impairments is likely to address a broader range of functional limitations encountered in everyday life. The results suggest that visual exploration and reading should not be treated as isolated rehabilitative domains; rather, integrated interventions may promote more generalized visual strategies applicable across multiple real-world contexts. Clinicians and researchers may therefore consider designing individualized training programs that incorporate text-based stimuli for patients who prioritize reading improvements alongside visual exploration, tailoring rehabilitation more closely to patients' specific goals. Allowing patients to choose between text-based and non-text-based tasks could further improve the personalization and effectiveness of visual exploration training.

From an efficiency perspective, training both visual exploration and reading within a single program is a more resource-effective approach, particularly given the limited time available for direct patient care to clinicians in neurorehabilitation settings (Macchiavello et al., 2024). This integrated approach may also improve patient adherence compared to separate or sequential interventions. Furthermore, because reading plays a vital role in daily life and is essential for independence, communication, and overall quality of life, improvements in reading ability may lead to better social participation, increased employability, and enhanced emotional well-being. Engaging with text-based stimuli may also stimulate broader cognitive functions such as attention, working memory, and language skills, and could potentially help prevent cognitive decline (Chang et al., 2021), a particularly relevant consideration for hemianopic patients with comorbid neurological impairments.

While these results are promising, future research is needed to confirm whether similar benefits can be replicated in clinical populations with HVFDs. The accessibility of this computer-based training program in patients with HVFDs is generally favorable but could be improved in several areas. First, the program is currently only available in German, limiting its reach to German-speaking populations. Translating the program into multiple languages would make it accessible to a wider audience. In terms of cognitive accessibility, the program is designed with simple instructions and rather short text-based stimuli, which should be manageable for most patients. The inclusion of auditory feedback after each search trial further

supports cognitive engagement. However, patients with motor impairments may struggle with interacting through a mouse or keyboard, making alternative input methods, such as voice commands, an important addition to enhance physical accessibility. Additionally, features like customizable text sizes would further enhance physical accessibility. Overall, the program is user-friendly and can be conducted both in clinical settings and at home. Yet, improvements in adaptability are needed, particularly in offering adjustable difficulty levels. Tailoring task complexity to individual patient abilities would prevent patients from feeling either overwhelmed or under-challenged.

In conclusion, our findings indicate that simultaneously addressing multiple functional impairments within a single training program enhances efficiency and promotes broader, more transferable skills relevant for daily living. Although the program is accessible and user-friendly, enhancements such as language translations, alternative input methods, and greater adaptability in task complexity could broaden its applicability and effectiveness for patients with HVFDs. Further research with this population is needed to confirm the benefits of combined training observed in our study.

### *3.2. Practical challenges in developing ecologically valid and transferable compensatory trainings*

While the training programs developed and tested in both studies demonstrated clinically relevant effects and were designed with accessibility in mind, several challenges emerged in creating interventions that are both ecologically valid and capable of promoting transferable improvements for patients with HVFDs.

In the first study, which involved a home-based VR visual search training, several technological limitations became evident. One of the primary challenges was the issue of image drift within the virtual environment. Stimuli sometimes shifted away from their intended spatial locations, likely due to the inherent limitations of the smartphone gyroscopes used in the initial VR headset. This issue was not observed when using a standalone Oculus Go headset, suggesting that the quality of the VR experience was heavily dependent on the underlying hardware. Additionally, problems such as strap loosening and reduced visual acuity at the periphery of the VR display—likely due to a lack of adjustable lenses—compromised user comfort. These experiences highlight a trade-off between accessibility and usability: while smartphone-based VR systems offer an affordable and widely accessible option, achieving greater precision and user comfort may necessitate investment in more expensive, higher-quality devices.

In terms of training design, we faced the challenge of balancing ecological validity with patient safety. Specifically, it was necessary to avoid stimuli that could potentially provoke cybersickness or epileptic

seizures, particularly given the vulnerability of neurologically impaired populations. As a precaution, the training used two-dimensional stimuli rather than complex three-dimensional scenes. However, current evidence suggests that the risks associated with 3D VR environments are lower than previously assumed. The medical literature does not support a heightened risk of photosensitive seizures linked to VR use (Tychsen & Thio, 2020), and studies such as by Prasad and colleagues (2012) have shown that 3D media rarely trigger seizures even in photosensitive individuals. Consequently, future VR-based rehabilitation programs could potentially integrate more immersive 3D environments to better simulate real-world scenarios. Although cybersickness remains a concern when patients navigate through 3D environments, it can be managed through strategies such as shorter session durations and frequent breaks (Simón-Vicente et al., 2024).

The combined visual search and reading training in the second study presented a different set of challenges. Designing an integrated task that used both word and pseudo-word stimuli required careful consideration of stimulus validity. A major challenge was ensuring that the pseudo-words created were truly nonsensical and not mistaken for dialectal or unfamiliar real words, which could confound task performance. To address this, we conducted a preliminary survey with colleagues unaffiliated with the study to validate the stimuli, discarding any ambiguous items that led to confusion.

Another design consideration involved the choice between single-word and sentence-based stimuli. While training with isolated words effectively targeted basic visual search and recognition skills, real-life reading typically involves more complex sentence processing. There were indications that the third part of the combined training featuring sentence stimuli was more challenging and differed more substantially from visual search training without text-based stimuli. This component may have contributed most to the greater reading improvements observed in the combined training group. If confirmed in future research, these observations would suggest that incorporating sentences rather than isolated words into integrated visual exploration and reading trainings may better support real-world reading abilities.

Overall, these challenges underscore the complexity of designing compensatory interventions that are not only accessible and safe but also ecologically valid and capable of promoting meaningful functional improvements in everyday life. Addressing issues related to technology limitations and stimulus validity will be critical for the continued development of effective neurorehabilitation programs for patients with HVFDs.

### *3.3. Methodological considerations*

The research presented in this dissertation revealed several important methodological challenges that bear directly on the design and interpretation of clinical trials evaluating the efficacy of compensatory visual exploration interventions. One of the most significant challenges encountered was establishing a suitable control condition. The first study was designed to compare the effects of a placebo training phase—where stimuli were presented on the side of the visual display corresponding to the patients' intact visual field—with those of the active training phases, which included eye and head movement training with stimuli presented on both sides of the visual display. Initially, the placebo training phase was conceived as a neutral baseline condition, intended to control for non-specific effects such as participant engagement and expectancy. It was assumed that the training itself would exert no measurable influence on the key outcome variables. However, this assumption proved to be flawed. As reflected in the descriptive data, the placebo training exerted a range of effects on visual search performance—some of which enhanced outcomes (faster search times, reduced number of saccades), while others were detrimental (reduced saccadic amplitude, increased saccadic asymmetry, and fewer first saccades into the blind hemifield). These findings complicated the interpretation of the EMT phase's efficacy. In cases where placebo training already improved performance, the scope for further improvement through EMT was limited. Conversely, where placebo training induced maladaptive changes, the EMT phase needed to overcome these negative effects, potentially obscuring or attenuating its true impact. In both scenarios, the influence of the preceding placebo training phase undermined the clarity of treatment effects attributable solely to EMT.

A closer examination of the placebo condition's design helps to explain its unintended effects. At the onset of each search trial, the stimuli were presented exclusively within the intact visual field, with the implicit assumption that this would not stimulate the blind hemifield. However, as participants shifted their gaze toward the intact visual field during training, some stimuli inevitably entered the blind field, triggering saccades toward that region and unintentionally providing exposure that activated compensatory mechanisms. Furthermore, the restricted spatial distribution of stimuli led to smaller saccades and contributed to an asymmetric scanning pattern, likely accounting for the post-training reduction in saccadic amplitude and the increased bias toward the sighted hemifield.

Thus, the placebo training functioned not as a truly inert condition, but rather as a simplified variant of visual search training. It inadvertently promoted some beneficial adaptations while reinforcing others that were maladaptive. These mixed effects raise a critical methodological issue: whether it is feasible to construct a placebo condition that is both psychologically credible and functionally inert in the context of visual rehabilitation. While it remains possible that the placebo training acted as a psychological placebo—given that most patients did not report perceiving any differences between this and subsequent training phases—the evidence suggests that it also had substantial behavioral effects. As such, its role as a neutral control is questionable.

These findings underscore the complexity of designing control conditions for cognitive and perceptual interventions. They highlight the need for careful piloting and a nuanced understanding of how even minimal exposure to task-relevant stimuli may engage learning or adaptation processes that are meant to be exclusively targeted by the active training condition. To address this challenge, future research should aim to develop more inert control tasks that maintain participant engagement and account for expectancy effects without engaging the visual search system. For instance, tasks such as letter or shape identification at fixation can match attentional demands without prompting saccadic exploration. Alternatively, tasks involving other modalities—such as auditory or tactile discrimination exercises—can serve as control activities that preserve engagement while eliminating overlap with the specific sensory-motor processes targeted by visual search training.

Beyond choosing different control tasks, methodological rigor can be strengthened through study designs that address confounds introduced by active placebo conditions. As in medical research, within-subject designs incorporating washout periods can minimize carry-over effects from placebo training, allowing for a clearer assessment of the active training's specific impact. When feasible, including multiple control groups (e.g., no-training, cognitive training, and placebo) offers a more robust framework for distinguishing intervention-specific effects from spontaneous recovery, general engagement or expectancy-related changes. Additionally, within-subject repeated-measures designs, such as multiple baseline protocols, offer a sensitive means of detecting subtle changes across both trained and untrained phases within individuals.

The selection of an appropriate control condition also emerged as a methodological concern in our second study. The choice of control, in this case, an exploration training devoid of text-based elements, may have attenuated the comparative effects of the combination training by inducing improvements in reading

performance. In line with prior findings on task-specificity and transfer effects in visual training programs (Schuett et al., 2012; Zihl et al., 2021; Postuma et al., 2024), we observed that the combination training, which included word stimuli, led to broader and more pronounced improvements in reading outcomes than the exploration training. Nevertheless, the exploration training—although lacking direct exposure to words—was not inert. It still resulted in significant gains in reading speed, even if accuracy remained unchanged. The exploration group also demonstrated significant post-training improvements in words per minute, our composite outcome measure that captures both reading speed and accuracy. However, combination training showed no advantage over exploration training on any outcome measure except words per minute, where it led to significantly greater improvement, indicating a clear comparative benefit.

These findings suggest that while task-specificity played a role in determining training efficacy, the boundary between specific and generalized transfer may be more nuanced. The exploration training did not involve left-to-right scanning or lexical processing per se, but the stimuli were nonetheless composed of discrete elements, somewhat analogous to letters or word-like configurations. Such structural features may have engaged perceptual or cognitive mechanisms that overlap with those required for reading, potentially explaining the observed improvements.

It remains speculative whether the use of an alternative control condition, such as a classic visual search training involving shapes or symbols entirely unrelated to word-like features, would have produced different results. Such a design might have further isolated the effects of combination training by removing even minimal structural similarities to linguistic stimuli. One might hypothesize that under those conditions, only the combination training would result in improved reading outcomes, while the control training would affect visual exploration exclusively. However, evidence from previous research tempers this assumption. For instance, Vialatte and colleagues (2023) demonstrated that symbol-based visual search training can enhance reading accuracy in dyslexic children, while Schuett and colleagues (2008b) reported that training with Arabic digit sequences was as effective in improving both reading performance and associated oculomotor behaviors as conventional text training. These studies underscore that improvements in reading do not strictly require text-based stimuli.

Taken together, our findings contribute to this evolving discourse by indicating that while word stimuli are not strictly necessary for reading improvements, their inclusion in visual search training yields broader benefits—specifically, gains in both speed and accuracy. Thus, the presence of word stimuli confers a

measurable comparative advantage, strengthening the case for their integration into rehabilitative training programs for patients with HVFDs.

### *3.4. Conclusions and outlook*

In this thesis, we aimed to explore and evaluate novel compensatory training approaches for individuals with HVFDs, focusing particularly on the development, feasibility, and preliminary efficacy of accessible, ecologically valid interventions that held the potential to generalize to everyday functional domains affected by HVFDs. To this end, we conducted two experimental studies that employed different but complementary training designs: one using a home-based VR visual search training for patients with HVFDs and the other combining visual search and reading training in a laboratory setting with simulated hemianopia.

The first study demonstrated that it is feasible to implement a home-based VR training program that can induce clinically relevant improvements in visual exploration. Participants showed significant enhancements in visual search performance following both active training phases compared to the performance after the placebo phase. Importantly, the study highlighted that expanding the visual display and encouraging head movements does not impair training outcomes—in fact, it may enhance ecological validity by approximating the naturalistic demands of visual exploration in real-world contexts. Moreover, the low drop-out rate and predominantly positive participant feedback indicated that even simple two-dimensional stimuli in a VR environment can yield an engaging and tolerable training experience for neurologically vulnerable populations.

In the second study, we tested a combined training approach that integrated reading and visual search components using text-based stimuli, which produced greater improvements in reading performance compared to an exploration-only control training. These findings suggest that incorporating text-based elements into compensatory training offers additional benefits, enhancing oculomotor function relevant for both visual exploration and reading.

Across both studies, we also encountered several practical and methodological challenges that informed our broader understanding of intervention development. Technologically, the VR-based training exposed limitations in hardware quality, such as image drift and reduced peripheral acuity with smartphone-based systems, underscoring the trade-off between accessibility and usability. In terms of design, ensuring stimulus validity and patient safety led to compromises, such as using 2D stimuli to mitigate risks of

cybersickness or seizures. However, emerging evidence suggests that 3D VR environments may be safely explored in future iterations with proper precautions (Tychsen & Thio, 2020; Prasad et al., 2012; Simón-Vicente et al., 2024).

Methodologically, the studies raised important considerations regarding the selection and design of control conditions. In both experiments, control training, originally intended as inert comparators, likely induced significant changes. For example, the placebo training in the VR study unintentionally encouraged saccadic adaptations, complicating the interpretation of subsequent training effects. Similarly, the exploration training in the second study, although devoid of text-based content, led to measurable improvements in reading speed. These observations underscore the need for more nuanced control strategies that avoid unintended engagement of target mechanisms.

Looking forward, future studies on compensatory visual exploration training for HVFDs should address several key gaps identified in this research. First, VR-based interventions should be tested in larger and more homogeneous clinical samples to more accurately assess their efficacy and generalizability. Using improved VR hardware and comparing outcomes to more inert control tasks (e.g., central fixation tasks or non-visual training modalities), or employing alternative study designs, would enhance the methodological rigor and better differentiate training-specific effects. Second, the effects of combination training incorporating reading elements should be directly tested in patient populations, to determine whether the improvements observed in healthy participants with simulated hemianopia extend to clinical groups with actual visual field loss. Third, the long-term durability of training effects remains an open question. Follow-up assessments are necessary to determine whether visual search and reading improvements persist over time and whether repeated booster sessions may be needed. Lastly, future research should more explicitly examine generalization to key ADLs through targeted evaluation.

In terms of broader implications for the field of visual rehabilitation, the present findings also offer several promising directions. First, the data support the feasibility of designing an engaging and effective exploration training that incorporates wider visual displays and head movements, countering the concern that increased motor demands might deter participants or reduce efficacy. Second, we showed that meaningful training gains can be achieved using simple, cost-effective 2D stimuli, which enhances the scalability of these programs for home-based use. Finally, our findings demonstrate the added value of integrating text-based content into visual training, suggesting that reading and exploration can be trained simultaneously to produce broader improvements. These insights contribute to a growing evidence base

that supports personalized, ecologically valid, and technologically supported rehabilitation strategies for individuals with HVFDs.

In conclusion, while challenges remain in optimizing and evaluating compensatory training programs, this thesis provides a solid foundation for future research and clinical innovation. By addressing both the practical constraints and methodological complexities identified here, the next generation of visual rehabilitation interventions can move closer to offering accessible and effective solutions for those living with visual field loss.

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<sup>2</sup> This list comprises only the references for the General Introduction and General Discussion. The references of the manuscripts contained in this thesis are listed at the end of corresponding chapters.

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## List of publications

Buchmann, I., Dangel, M., Finkel, L., Jung, R., Makhkamova, I., Binder, A., Dettmers, C., Herrmann, L., Liepert, J., Möller, J. C., Richter, G., Vogler, T., Wolf, C., & Randerath, J. (2020). Limb apraxia profiles in different clinical samples. *The Clinical Neuropsychologist*, 34(1), 217–242. <https://doi.org/10.1080/13854046.2019.1585575>

Krewer, C., Makhkamova, I., Boettcher, A., Jahn, K., & Mueller, F. (2019, May). *Personalized stimuli in the assessment of consciousness using the Coma Recovery Scale-Revised (CRS-R) in the motor and communication subscales* [Conference abstract]. International Brain Injury Association's 13th World Congress on Brain Injury, Toronto, Canada.

## Author Contributions

**Manuscript 1:** Exploring New Frontiers: VR-Based Visual Search Training for Patients with Homonymous Visual Field Deficits. Inara Makhkamova, Doris Schmid, Thomas Schenk

I.M. and T.S. conceived the project; I.M., D.S. and T.M. designed experiments; I.M. recruited patients and collected the data; D.S. partially assisted with patient recruitment and data collection, T.S. supervised research; D.S. wrote the code for the pre-and post-training tests, including pre-processing of output data; I.M. analyzed and interpreted data; I.M. wrote the manuscript with input from T.S.

### My contribution in detail:

For this manuscript, I contributed to the conceptualization of the study and the development of the overall methodology. I was responsible for recruiting patients and collected the majority of the study data, including screening evaluations, neuropsychological assessments, training data, and pre- and post-training assessments. I provided instruction and support to participants on the use of the training software and VR headset, assisting with any issues that arose during their participation. In addition, I managed the curation and organization of the data, conducted data analysis and interpretation, and created the visualizations used in the manuscript. I was the author of the original draft and contributed to its review and editing following feedback from T.S.

**Manuscript 2:** Evaluating the Efficacy of Combined Reading and Exploration Training in Simulated Hemianopia. Inara Makhkamova, Doris Schmid, Thomas Schenk

I.M. and T.S. conceived the project; I.M. designed and programmed the training, including the hemianopia simulation; I.M. recruited participants and collected the data; T.S. supervised research; D.S. wrote the code for the pre-and post-training tests, including pre-processing of output data; I.M. analyzed and interpreted data; I.M. wrote the manuscript with input from T.S.

My contribution in detail:

For this manuscript, I contributed to the study's conceptual framework and methodology. I developed the combination and exploration training protocols and implemented the gaze-contingent hemianopia simulation mask within both the training sessions and the pre- and post-training evaluations. My responsibilities also included participant recruitment and managing all aspects of data collection, covering both the training phase and assessment stages. I carried out data analysis and interpretation, and created the figures and visualizations featured in the manuscript. I wrote the initial draft and participated in the review and editing process based on feedback from T.S.