The Dynamics of Eye Dominance and Its Implication for 3D Interaction

Franziska Prummer, BA, MSc

School of Computing and Communications

Lancaster University

A thesis submitted for the degree of

Doctor of Philosophy

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Abstract

Eye dominance is a behavioral concept that describes the asymmetry between the eyes, in which one eye contributes more to visual input than the other. This difference between our eyes offers perceptual advantages and shapes how we interact with our surroundings. It is a long-standing concept in vision science and psychology, yet its role in human-computer interaction (HCI) remains underexplored for interaction and interface design.

This thesis investigates the fundamental behavior of eye dominance and its potential applications in 3D interaction. It examines eye dominance through its theoretical grounding in fields such as vision science and psychology, its current treatment within HCI, its objective measurement, and discusses opportunities for effective application. A mixed-methods approach combining a systematic literature review with virtual reality (VR) user studies employing eye tracking explores both contextual factors that an HCI designer might exploit and individual characteristics to consider when leveraging eye dominance in HCI.

The results demonstrate the dynamic and nuanced nature of eye dominance across tasks, with patterns unique to each individual. Specifically, eye dominance was influenced by both user-centric and context-specific factors, such as viewing angle, visual acuity, and the hand used for alignment. In addition, traditional testing methods yielded inconsistent results, highlighting limitations of established procedures. To reliably capture eye dominance patterns, we developed an in-HMD classification method and a machine-learning prediction model designed specifically for VR contexts. Based on these findings, practical guidelines for implementing eye dominance effectively are provided. This thesis positions eye dominance as both a research challenge and an opportunity for interaction design, and reflects how acknowledging this dynamic visual asymmetry can inform more effective and adaptive interfaces and interactions for 3D environments.

Acknowledgements

This thesis would not have become what it is without the support and encouragement of many people throughout this journey.

First and foremost, I would like to express my deepest gratitude to my supervisor, Prof. Hans Gellersen, who shared my excitement for this project from the beginning on. His guidance, encouragement, and trust in my ideas have been invaluable throughout this journey. I am especially thankful for the environment he created, in which research is treated as a passion and curiosity and creativity are able to thrive.

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To my siblings Philip and Katharina, for visiting me, cheering me on from near and far, and always bringing a sense of home whenever I needed it most. Your support, humor, and presence have been a steady reminder of what truly matters.

And to my friends, old and new, thank you for sharing in my excitement for this project and for never growing tired of my countless explanations of eye dominance, research studies, and experimental setups. Your curiosity, encouragement, and companionship meant more to me than you know.

Declaration

I declare that the work presented in this thesis is, to the best of my knowledge and belief, original and my own work. The work of this thesis was done under the supervision of Professor Hans Gellersen at Lancaster University's School of Computing and Communications. The material has not been submitted, either in whole or in part, for a degree at this, or any other university. This thesis does not exceed the maximum permitted word length of 80,000 words including appendices and footnotes, but excluding the bibliography. A rough estimate of the word count is: 39819

Franziska Prummer

Contributing Publications

The following publications have been created directly from the thesis, from which large portions of this published work are used:

Franziska Prummer, Ludwig Sidenmark, and Hans Gellersen. "Dynamics of Eye Dominance Behavior in Virtual Reality". In: *Journal of Eye Movement Research* 17.3 (2024), pp. 10–16910. DOI: 10.16910/jemr.17.3.2(Chapter 3)

Franziska Prummer, Florian Weidner, and Hans Gellersen. "Advancing Eye Dominance Testing: Comparing Traditional Methods with an In-HMD Approach for AR/VR Applications". In: *2025 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. 2025, pp. 112–116. DOI: 10.1109/VRW66409.2025.00030(Chapter 4)

Franziska Prummer, Mohamed Shereef Abdelwahab, Florian Weidner, Yasmeen Abdrabou, and Hans Gellersen. "It's Not Always the Same Eye That Dominates: Effects of Viewing Angle, Handedness and Eye Movement in 3D". in: *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*. CHI '25. New York, NY, USA: Association for Computing Machinery, 2025. DOI: 10.1145/3706598.3713992(Chapter 5)

Franziska Prummer, Florian Weidner, and Hans Gellersen. "All But Static: Exploring Dynamic Eye Dominance for Foveated Rendering". In: *2025 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. 2025, pp. 376–380. DOI: 10.1109/VRW66409.2025.00087(Chapter 8)

The following chapters have been accepted or are under review:

Chapter 2: Submitted to ToCHI

Chapter 6 & 7: Accepted to 2026 ETRA COGAIN Workshop

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Chapter 1

Introduction

This thesis explores eye dominance behavior in the context of human-computer interaction (HCI) and interactive 3D environments. Visual perception plays a central role in HCI. Fundamental visual concepts such as perspective, pointing, aligning, and line-of-sight are deeply embedded in how we interact with computing systems. As such, a solid understanding of visual perception is essential for HCI research. One underexplored but influential aspect is *eye dominance*. This behavioral trait encompasses a preference for one eye over the other, often experienced in daily tasks such as alignment. While fields such as vision science and psychology investigate eye dominance more deeply, a holistic and thorough understanding of the behavior has not yet been transferred into HCI. Although some work has leveraged or tested eye dominance in HCI, additional features it holds are missed. We review foundational insights from vision science and psychology and explore how interactive 3D environments benefit from implementing eye dominance. Furthermore, we develop and evaluate eye dominance testing methods for VR contexts, and explore how eye dominance changes in response to both contextual and individual factors.

1.1 Binocular Vision and Depth Perception

As humans, we see with two eyes, a phenomenon known as binocular vision. Both eyes work in unison to create the 3D world we perceive and interact with. Due to the two different vantage points, each eye creates an individual image, which is then fused in the brain [118]. This is referred to as *binocular disparity*, and is determined by the horizontal distance between our eyes, our *inter-pupillary distance* (IPD) (cf. Figure 1.1). To us, it seems as if we perceive the world from a single midpoint between our eyes, the so-called *cyclopean eye* [33]. However, both eyes do not contribute equally to our visual input [134]. Addressing this asymmetrical visual processing of our eyes enables the design of interactions that align with how users actually see and interact.

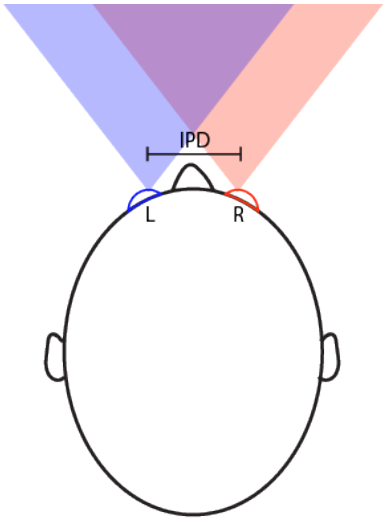


Figure 1.1: Illustration of Binocular Vision (top-down view). Each eye (left and right) captures a separate image due to the inter-pupillary distance (IPD).

1.2 Eye Dominance Overview

The asymmetry in the visual system and preference of visual input of one eye is known as *eye dominance*, specifically *sighting dominance*. It shapes how we interact with and see the world around us. In practice, one eye contributes more strongly to perception or control than the other, reflecting an asymmetry in how the visual system integrates input from both eyes [79, 16]. Its effect is particularly noticeable during tasks like distance pointing, where individuals align the target and finger with their dominant eye [60, 105, 80]. The dominant eye also shows a perceptual advantage: it perceives objects as larger and sharper [23, 109, 75], is faster during horizontal saccades [131], and tends to guide posture [10, 39]. Leveraging this behavioral trait will open opportunities for interaction design. While other forms of eye dominance, such as acuity (the eye providing clearer vision) and sensory dominance (the leading eye during competing visual input), exist, these fall outside the scope of this work.

1.3 Research Challenges

HCI systems are often modeled under the assumption that both eyes contribute equally to our visual perception and that our line of sight originates from the midpoint between our eyes, the so-called 'cyclopean eye'. However, the research in vision science has shown the contrary: one eye tends to contribute more to spatial judgments and interactions than the other, affecting both our perception and behavior. This introduces perceptual issues when interacting in our 3D environments. Our binocular disparity can create conflicting spatial cues, such as

double vision. In practice, this means when pointing at or aligning distant objects, while focusing on either the close or distant object, the other will appear double and vice versa. Similarly, parallax is a phenomenon in which an object appears to be placed slightly differently from where it actually is located. Resulting from the two slightly different images produced by each eye, and depending on which eye is closed, objects appear shifted relative to the background (cf. Figure 1.2). Yet when interacting normally and binocularly, the dominant eye's input is preferred which biases our interactions such as pointing. As a consequence, interface elements, depth perception, and interaction accuracy are affected. When designing and evaluating visual systems, individual eye dominance needs to be considered to mitigate these perceptual challenges.

(a) (b)

Figure 1.2: Visual representation of parallax during pointing. Because the same object is viewed from two different perspectives (left and right eye), an apparent displacement relative to the background occurs. a) When viewing from the left eye, the finger is perceived on the object. b) When viewing from the right eye, the finger is perceived next to the object.

This work proposes that eye dominance represents a meaningful design dimension in immersive systems, with implications for usability and interaction accuracy. In 3D environments such as virtual and augmented reality (VR/AR), eye dominance can influence how users interact with content. These technologies require precise, naturalistic interactions, where alignment is often crucial, for example, during tasks such as pointing and selecting. Aligning virtual objects with the dominant eye rather than the cyclopean eye can offer more intuitive depth perception [141]. Calibrating a virtual cursor or an image-plane selection technique to the users dominant eye (the effective visual vantage point during pointing and alignment) would enhance selection accuracy and user comfort [47, 141]. Similarly, prioritizing the dominant eye in tasks such as foveated rendering can enhance system performance and lower device energy consumption [86].

	Research Question	**Chapter**
RQ 1	What is eye dominance, and what potentials for application in human-computer interaction does it offer?	2
RQ 2	How does eye dominance behave during interaction in 3D environments?	3 & 4 & 5
RQ 2a	How can eye dominance be objectively measured and characterized in 3D environments?	3 & 4 & 6
RQ 2b	Which factors influence eye dominance and how does it change in 3D interaction?	3 & 5 & 6 & 7
RQ 3	Can we predict eye dominance in 3D interaction?	7

Table 1.1: Overview of Thesis Research Questions and Relevant Chapters

Given the present understanding within HCI, eye dominance is routinely compared to handedness, which is often considered as a static and unchanging trait. Yet previous work from psychology has unveiled the opposite, demonstrating a dynamic behavior [58]. Eye dominance can change with the angle of horizontal viewing. For instance, when looking or fixating at an object far to the left, while maintaining a centrally fixed head position, the left eye will become dominant. In turn, when looking at a target at a right horizontal viewing angle, the right eye is dominant. Despite this first evidence of flexibility, little is known about how it behaves in interactive environments. Understanding which eye dominates and how it changes will open further opportunities for interaction design.

1.4 Research Aim and Questions

The aim of this thesis is to understand and explore the dynamic nature of eye dominance and how it can be leveraged for 3D interaction. Table 1.1 provides an overview of the leading research questions and the corresponding chapters of this thesis.

The first research question (**RQ 1**) concerns the conceptual understanding and state of the art of eye dominance, as well as its current applications in the HCI field. Eye dominance is frequently studied in disciplines such as psychology or vision science. Yet, it is applied in HCI in a limited way: it is seen as too simplistic, and its benefits are often overlooked. The discrepancy between how HCI defines eye dominance and how expert fields such as psychology and vision science define and study it limits its potential for successful application. Prior work has shown a dissimilarity between the dominant and non-dominant eye. Whether perceptual or behavioral, this demonstrates that the two eyes are not the same. By uncovering the foundational behavior of eye dominance, the perceptual advantages is holds, and what it is not, we can guide these insights into actionable outcomes.

Additionally, by synthesizing how eye dominance is currently implemented or reflected in HCI work, we identify its application potentials. With this in mind, and connecting the perspective and knowledge of fields outside HCI, we can establish a more comprehensive understanding of eye dominance. This enables identification of gaps in current HCI research and informs design and research for 3D environments.

The second question (**RQ 2**) investigates the characteristics of eye dominance and provides foundational insights into its behavior in 3D contexts. To address this question in detail, two sub-questions are composed.

RQ 2a concerns measurement and methodology. Examining how eye dominance behaves requires a robust testing procedure. Vision research provides a multitude of testing methods with variability in procedure and parameters. However, the majority of these tests rely on subjects indicating what they see; an objective measurement procedure designed specifically for virtual 3D contexts is absent. With this research question, we aim to develop a reliable, easy-to-use testing method that does not require participants' subjective reports of what they see. Ultimately, we aim to detect the natural eye dominance behavior and how people align and point with reference to the individual eyes eye.

RQ 2b focuses on the determinants of changes in eye dominance. Within vision science, eye dominance is known to be influenced by individual factors, such as hand preference or heritability. Further literature also suggests that contextual factors affect eye dominance. Notably, the work by Khan and Crawford [58] suggested that eye dominance changes with the horizontal viewing angle. This raises the question, which further factors induce a reversal of eye dominance? In what way are they relevant for interaction in immersive environments? Identifying both individual and contextual factors that influence eye dominance allows us to highlight features that HCI designers must consider, versus factors that can be leveraged when implementing eye dominance.

Finally, **RQ 3** explores how eye dominance can be predicted for 3D interactions. Building on previous questions, we examine whether factors influencing eye dominance can serve as features in a predictive model. In particular, we aim to explore which features are most predictive and whether context-specific features alone are sufficient for accurate prediction. Such a model could enable systems to automatically infer a user's dominant eye, eliminating the need for previous testing.

1.5 Research Scope

This thesis focuses on understanding eye dominance in HCI. We particularly focus on *sighting dominance*, a behavior mostly connected with pointing and visual alignment. These tasks are particularly relevant to 3D contexts, where both perception and motor coordination are essential. While both acuity and sensory dominance play a role in perception, the scope of this work is limited to the type

that involves motor coordination. To connect the understanding of eye dominance from both a perception and interaction perspective, this work draws on theories and methods from multiple fields, including vision science, psychology, and HCI.

1.6 Methodology

A mixed-methods approach addresses the key research questions, thoroughly exploring eye dominance behavior and its potential applications in HCI. By employing a systematic literature review with qualitative analysis, this study provides insights into how the behavior is understood, discussed, and defined in both expert fields and HCI. With this approach, patterns, themes, and concepts surrounding eye dominance are uncovered. Subsequent user studies were conducted in VR using eye tracking, with a quantitative focus on analyzing and measuring behavior in action. This enabled the development of eye dominance testing methods tailored specifically for virtual 3D environments, while testing theories and examining relationships among variables. Furthermore, the collected data were used for prediction and model development. Detecting which eye is dominant at any given moment can inform an enhanced, more accurate user experience. The mixed-methods approach enabled the capture of both theoretical and practical insights into eye dominance, providing a comprehensive understanding.

The first practical experiment replicated and extended a study of Khan and Crawford [58]. In their results, eye dominance varies with the horizontal viewing angle. The study design was reproduced within a VR environment. Using both the controller and eye tracking, we objectively determined the dominant eye using a geometric approach. Furthermore, this study examines whether the original study's results extend to VR environments and investigates the role of target distance.

From the initial experimental study and from the broader literature outside HCI, we discovered that a thorough theoretical understanding of eye dominance was necessary. Hence, a systematic literature review was planned and conducted, which serves as the related work section of this thesis. Drawing on theoretical foundations from expert fields such as vision science and psychology, we synthesize the core features and factors that underpin the behavior. Furthermore, by analyzing HCI literature, we gain insight into the current understanding and practical implementation of eye dominance. From this, we aim to guide and inform HCI designers for effective implementation.

Following the literature review and our first experimental study, we compared traditional eye dominance tests with our testing method designed specifically for VR contexts. Using our newly developed VR testing method, we explored additional variables influencing eye dominance, that had not yet been examined and are relevant to interactions in immersive environments. We examined the impact of viewing angle, handedness, and eye movements (random saccades, sequenced saccades, and smooth pursuits) on eye dominance. This strengthens previous

findings in static scenarios and extends them to dynamic settings — essential for leveraging eye dominance in HCI and AR/VR. Based on lessons from our prior experiment, we adjusted our eye dominance classification metric to support more naturalistic behavior in XR settings.

This was followed by a study in which we firstly explored the additional vertical dimension as a factor influencing eye dominance. Although most interactions in XR occur at eye level, gaze shifts and interactions above and below eye level do occur.

In the next step, we investigated predictive factors of eye dominance and examine the feasibility of a predictive machine learning (ML) model. Previous results reveal individual eye dominance behaviors and switches, indicating that simplistic, general models that apply to the broader population are inadequate. This work provides insight into which individual and contextual factors should be considered when tailoring XR experiences to enable seamless and precise interactions.

This thesis includes material from several publications, as listed in Contributing Publications. I served as the first author on these publications, leading the study, analysis, and writing.

1.7 Contributions

This thesis makes the following theoretical and practical contributions:

- **Introduction of eye dominance for HCI.** Although well-studied in vision science, the understanding of eye dominance in the HCI field remains limited. This is the first in-depth study into eye dominance within HCI. We discuss the relevance and benefits of eye dominance for 3D environments to enhance interaction and user experience.
- **Conceptualization of eye dominance for 3D environments.** This work conceptualizes eye dominance as a dynamic, task-dependent trait that changes in response to both individual and contextual factors. Drawing on fields such as vision science and psychology, we identify gaps in HCI research.
- **Eye dominance testing procedures for VR.** This work reveals the lack of standard testing procedures for eye dominance and demonstrates that established methods yield inconsistent results. In response, building on insights from vision science and acknowledging the complexity of assessing eye dominance, this work introduces an in-HMD testing approach tailored for virtual 3D environments.
- **Eye dominance prediction model for VR.** Leveraging eye dominance requires methods to infer which eye dominates at any given moment automatically. Building on our results, we develop a machine learning (ML) prediction model for eye dominance that incorporates both individual and contextual

predictive features. This allows for the implementation of eye dominance and dynamic adaptation to changes within immersive environments.

- **Theoretical and practical guidelines for HCI work leveraging eye dominance.** Based on our work, we provide methodological and design-oriented recommendations when working with eye dominance in HCI. We provide guidance on the following:
  - **Reliable eye dominance testing procedures.** Traditional tests for eye dominance present inconsistent results between different procedures and require subjects to indicate what they perceive. We provide practical recommendations for using and reporting traditional testing procedures.
  - **Recommended individual factors for HCI designers to consider.** We provide theoretical foundations on individual (user-specific) factors that influence eye dominance within a 3D context. We recommend considering these factors, such as handedness or visual acuity, when designing interfaces and interactions with the dominant eye in mind.
  - **Contextual factors for HCI designers to leverage.** Contrary to individual factors, contextual factors are application and task-specific, such as viewing angle. These are task conditions that can be adapted dynamically to enhance performance or comfort.
  - **Potential applications of eye dominance for 3D interaction.** We synthesize and summarize potential applications of eye dominance in interactive 3D environments, including content or cursor placement, image-plane pointing, and foveated rendering.

1.8 Thesis Structure

To address the key research questions, this thesis is structured as follows:

Chapter 2 provides relevant background literature and addresses the first research question within a systematic literature review. By reviewing articles from both vision science and HCI, we synthesize information on the functionality and dynamics of eye dominance. Chapter 3 presents the first study, replicating and extending existing work on eye dominance into VR. Here, we examine whether the pattern of dynamic eye dominance in response to horizontal target angle and handedness also applies in VR settings, and we introduce target distance as a variable. Moreover, within this chapter we created a first objective method for testing eye dominance within VR environments. Based on the lessons learned of the first experimental study, Chapter 4 compares traditional eye dominance testing methods with a refined in-HMD testing method for VR contexts. Building on the previous chapters, Chapter 5 explores further variables influencing eye dominance, including target behavior and with that, eye movement types, as well as order effects in a study

with three individual tasks. Chapter 6 explores the effect of the additional vertical dimension of target location on eye dominance within an experiment. In Chapter 7, we train and evaluate a ML model to predict eye dominance from individual- and target-based features. Chapter 8 discusses the work presented in this thesis, in context of the main research questions. Furthermore, this chapter outlines research opportunities, highlights the potential benefits, and provides guidelines for integrating eye dominance in interactive 3D environments. Lastly, Chapter 9 presents the conclusion of this thesis.

Chapter 2

Systematic Literature Review

To understand eye dominance holistically and explore the application potentials for HCI, we synthesized information from fields that have explored this behavior in depth, addressing **RQ1**. While a few HCI studies have considered eye dominance in their designs [86, 47, 120], these efforts are still rare and narrowly focused (although promising). In contrast, vision science has long treated eye dominance as a core subject, offering a rich body of insights that is still underutilized in HCI. This disconnect between HCI and vision science marks a missed chance. Vision science offers theoretical and empirical insights that HCI can leverage to inform and enhance the design of user interfaces and interaction techniques. This chapter sheds light on what eye dominance is (and what it is not), how it can be measured, how it has been operationalized, and the opportunities it presents for HCI. To do this, we conducted a systematic literature review with three core questions in mind:

- What is eye dominance?
- How is eye dominance reflected in HCI?
- What can HCI learn from vision science?

We analyzed 166 articles on eye dominance, comparing how it is conceptualized and employed in both vision science and HCI. For both domains, we extract and synthesize definitions and testing methods to compare the understanding of eye dominance across fields. In addition, we prompt distinct questions within each field: In vision science, we investigate the fundamentals of eye dominance: which factors influence it, its effects on visual perception, and how it relates to other types of dominance. In HCI, we examine the motivations for considering eye dominance, how it is operationalized in interactive systems, and what effects it has during user interaction. The objective with this approach is to fill the knowledge gap within HCI by leveraging insights from vision science and to identify directions for future research and applications.

2.1 Materials and Methods

To review how eye dominance is considered in HCI and what we can learn from vision science, we followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [98]. The literature search was performed from 27.11-14.12.2023, screening was completed in February 2024, and the data analysis was completed in March 2024.

2.1.1 Search Terms and Databases

Our literature review was divided into two parts: one exploring vision science articles and the other on HCI work. To investigate the fundamentals of eye dominance in the first part (Section 2.3), we exclusively conducted our literature search on vision science articles. Considering this, we selected Scopus, WebOfScience, and PubMed as our primary databases. Table Table 2.1 presents the individual search queries for each database, along with the corresponding search results.

We used the keyword search provided by each digital library. Our search strategy utilized a combination of carefully selected keywords to identify studies related to eye dominance. The chosen keywords, such as "eye dominance", "dominant eye", "ocular dominance", and "sighting dominance", were selected based on their relevance to the topic under investigation. The search keywords were applied only to titles, abstracts, and keywords. The PubMed, Scopus, and WebOfScience search queries included "NOT" keywords to filter papers irrelevant to our research question. By excluding terms such as "animals", "rats", "monkeys", "surgery", "myopia", "cortex", and "strabismus", we could eliminate a large number of studies not relevant to our research focus.

To analyze HCI work that incorporates eye dominance within the second part of our review (Section 2.4), we used the digital libraries of ACM and IEEE as our primary search databases. Given the small number of results in these libraries, exclusion keywords were unnecessary. Furthermore, the included keywords were applied within the "All" search query. This ensured that studies not mentioning eye dominance in their abstracts or titles were included, even though they still applied standard eye dominance testing. These papers were included in our selection because they allowed us to analyze the motivation for including eye dominance testing in HCI work, the methods they use, and how they interpret the results.

Following this search strategy, 4680 papers were initially identified from the combined database searches, of which 299 duplicates were removed. This resulted in screening 4381 titles and abstracts using carefully selected criteria.

Table 2.1: Search queries for each database and search results

Database	Search Query	Search Result
PubMed	eye dominance[Title/Abstract] OR "dominant eye"[Title/Abstract] OR "sighting dominance"[Title/Abstract] OR "ocular dominance"[Title/Abstract] NOT "animals"[Title/Abstract] NOT "rats"[Title/Abstract] NOT "monkeys"[Title/Abstract] NOT "surgery"[Title/Abstract] NOT "myopia"[Title/Abstract] NOT "cortex"[Title/Abstract] NOT "strabismus"[Title/Abstract]	963
Scopus	TITLE-ABS-KEY ("eye dominance" OR "dominant eye" OR "sighting dominance" OR "ocular dominance" AND NOT "animals" AND NOT "rats" AND NOT "monkeys" AND NOT "surgery" AND NOT "myopia" AND NOT "cortex" AND NOT "strabismus")	1588
Web of Science	TS = ("eye dominance" OR "dominant eye" OR "sighting dominance" OR "ocular dominance" NOT "animals" NOT "rats" NOT "monkeys" NOT "surgery" NOT "myopia" NOT "cortex" NOT "strabismus")	1657
ACM	[All: "eye dominance"] OR [All: "dominant eye"] OR [All: "ocular dominance"] OR [All: "sighting dominance"] OR [All: "binocular parallax"]	135
IEEE	"eye dominance" OR "dominant eye" OR "ocular dominance" OR "sighting dominance" OR "binocular parallax"	337

2.1.2 Screening

When screening, we applied specific inclusion and exclusion criteria under the PICOC framework (Population, Intervention, Comparison, Outcome & Context) to ensure the retrieval of relevant studies while excluding irrelevant ones. We defined explicit inclusion and exclusion aspects within each criterion, as presented in Table 2.2. These were manually applied when reading the title and abstract of each paper.

We classified a study as clinical if it was conducted in a medical setting or involved specific patient populations with conditions affecting vision such as amblyopia, cataracts, or neurological impairments. This criterion enabled filtering of articles that were outside the scope of this review. Furthermore, we excluded studies that did not consider, evaluate, test, or discuss eye dominance in any meaningful way. However, we included reviews and commentaries when they contributed to understanding how the concept of eye dominance is defined, interpreted, or assessed across domains. An article was also automatically excluded whenever it was not written in English or was not a complete paper. Three people were involved in

Table 2.2: Inclusion and exclusion criteria following the PICOC scheme

PICOC	Inclusion	Exclusion
Population	Healthy Adults	Clinical Population or Patient Groups, not Humans
Intervention	Foundational studies, reviews or commentaries on eye dominance and related factors or perception, studies related to measurement or classification of eye dominance	Clinical studies, studies not addressing eye dominance, studies not related to vision science or HCI, Neural Computation or Modeling, Algorithms
Comparison	Studies investigating different methods or factors influencing eye dominance, comparing individuals with different levels or types of eye dominance	Studies not comparing different methods or factors, no implementation, or evaluation of eye dominance
Outcome	Methods to determine eye dominance, factors influencing eye dominance, operationalization or reflection of eye dominance in HCI (design consideration, eye tracking technology utilization, investigation of performance or perception)	Studies not presenting methods or techniques for determining eye dominance, lacking substantial information or findings relevant to the research questions
Context	Studies examining prevalence, experimental studies assessing different testing methods, studies investigating influences and perceptions of eye dominance in HCI design	Inadequate sample sizes, and poor methodology that compromises the reliability of findings related to eye dominance

the screening and analysis process. Critical papers were discussed and resolved in a consensus meeting. By examining the reference lists of the selected papers (backward snowballing), we identified and included additional relevant studies, ensuring comprehensive coverage of the topic. Figure 2.1 illustrates the article selection process via databases, from identification, through screening (eligibility assessment), to final inclusion.

2.2 Analysis and Synthesis

This literature review is structured into two parts, separated by discipline. The first part (Section 2.3) explores the holistic concept of eye dominance within vision science. The second part (Section 2.4) focuses on how eye dominance is addressed and implemented in HCI work, drawing directly from HCI literature. Hence, we categorized selected articles into 'Vision Science' and 'HCI' work.

Papers categorized to 'Vision Science' included foundational studies investigating measurement/classification techniques, perception and performance, and influences on eye dominance. The primary indicator of whether a paper was from this category

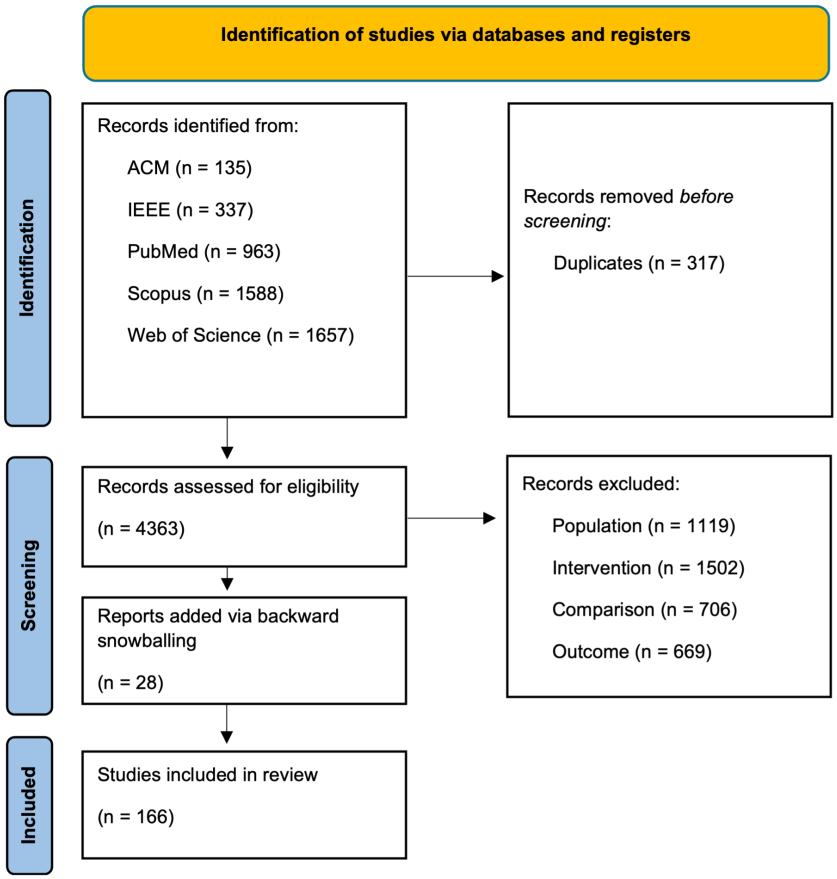


Figure 2.1: PRISMA Flowchart: Summary of selection process

was its publication venue. These were journals or conferences related to Optometry, Ophthalmology, Vision Research, Neuroscience, Psychology, or a similar field.

A paper was categorized as 'HCI' work whenever the publication venue of the article was related to the HCI field. This included CHI or ToCHI, Journal of Display Technology, IMWUT, or a computer science-related publication venue. A paper was also considered for the 'HCI' category whenever eye dominance was implemented in designing, developing or evaluating an interactive system. We searched for common patterns within studies and the key assumptions relating to eye dominance on which they are based. We were also interested in any HCI work that conducted an eye dominance test in their study.

2.2.1 Final Selection

Our final selection consisted of 166 articles ranging from the publication years 1929 to 2024. Of these, 28 papers were added to our selection by backward-snowballing. Figure 2.2 shows the distribution of the publication years of our sample, separated into Vision Science articles and HCI work.

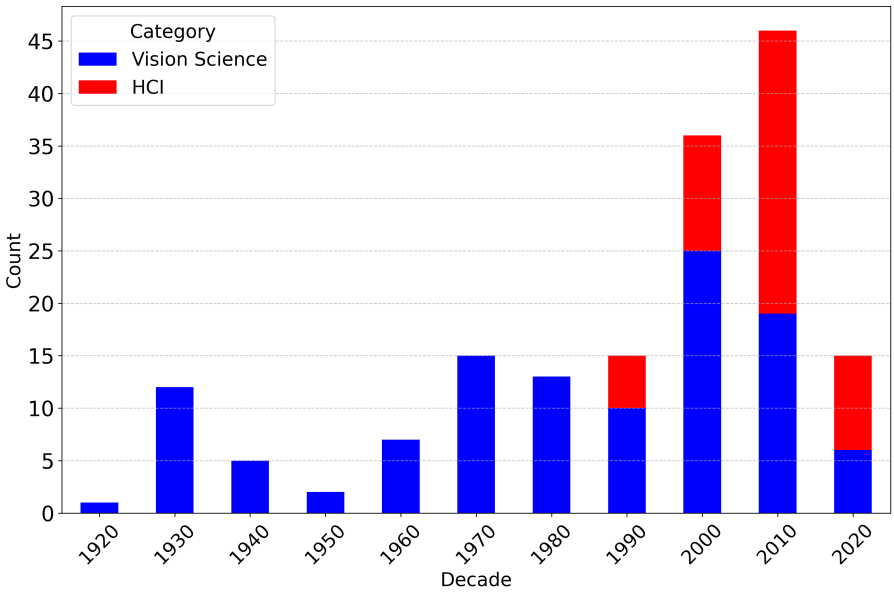


Figure 2.2: Distribution of Publication Years for Selected Articles, Grouped by Decade

A sum of 114 papers have been categorized into 'Vision Science' papers. Of these, 3 were meta-analyses on eye dominance, and 5 were reviews or commentaries. Publication venues include journals of various disciplines, such as psychology, vision research, ophthalmology, and neuroscience.

A total of 52 studies have been classified as HCI work. Of these, 9 were published in CHI and 2 in ToCHI. Other publication venues included ETRA, UIST, IMWUT, and TAP. A full list of these articles is found in the supplementary materials.

2.2.2 Analysis Frameworks

We developed two separate coding frameworks to operationalize themes and topics that closely reflected our research questions and aims of understanding eye dominance, its reflection in HCI, and what HCI can learn from vision science. Table 2.3 presents the framework for vision science, and Table 2.4 the framework for HCI articles.

We examined the concept holistically to understand the inherent nature of eye dominance, encompassing theoretical definitions, testing practices, and perceptual effects from an expert perspective. We aimed to generate a clearer understanding of the concept and its variability by synthesizing vision science results on the contextual and individual factors that influence eye dominance. With a multifaceted and holistic view, we can generate guidelines for an HCI designer to consider when designing with the dominant eye in mind. On the other hand, exploring the effects, performance differences, and correlations with different types of eye dominance,

Table 2.3: Analysis framework for vision science articles

Item	Description
Definition	How was eye dominance defined?
Testing Method	What was the method to determine eye dominance?
Contextual Influencing Factors	What are contextual factors that influence eye dominance?
Individual Influencing Factors	What are the individual factors that influence eye dominance?
Effects	What are the effects of eye dominance? In what way does the performance of the dominant eye differ?
Relation to Eye Dominance Types	How do the results relate to other eye dominance types (acuity or sensory dominance)?

as reflected in vision science work, allows us to understand which aspects an HCI designer can leverage to optimize interface design and interactions. We aimed to understand the current state of eye dominance research in HCI by examining how it has been motivated, considered, and implemented in past and recent studies and by evaluating the reported outcomes.

The analysis frameworks share some similarities, allowing for a thorough comparison of the understanding of eye dominance within the fields of vision science and HCI. Extracting information on eye dominance definitions within both fields enabled a comparison between how the concept is defined in vision science versus how it is understood in HCI. In both frameworks, we compared information on eye dominance testing methods. From a vision science and thus expert perspective, we aimed to understand the different testing methods and their outcomes. By observing the current testing approaches in HCI, we can identify discrepancies in methodology, assess the validity of their outcomes, and reflect on the implications.

Each article from vision science and HCI was read thoroughly, and relevant information was sorted into the corresponding framework category. For instance, whenever eye dominance was defined in an article, the relevant passage was inserted into the corresponding column “definition” within an Excel document. The categorization of coded results followed an inductive approach. This process led to specific observations, which we then generalized into broader themes.

2.3 Eye Dominance in Vision Science

The oldest article included in this analysis was published in 1929 in the Journal of Experimental Psychology [87]. Within this work, Miles presented his A-B-C Vision Test to determine ocular dominance. Earlier papers primarily investigated methods to determine sighting or eye dominance, whereas newer studies intend to study eye dominance and its behavior more deeply. Contemporary research examines

Table 2.4: Analysis framework for HCI articles

Item	Description
Sighting Dominance Definition	How was eye dominance defined?
Motivation	What was the main reasoning for considering/implementing eye dominance?
Testing Eye Dominance	Was eye dominance tested? If so, what test was used, and how was it described?
Consideration or Implementation	In what way was eye dominance considered or implemented?
Impact	What were the results/impacts of implementing or considering eye dominance?

possible factors that affect or influence eye dominance and vice versa, displaying eye dominance as a dynamic rather than permanent behavior. Within our selection of articles, 16 papers from 1929-1971 specifically explored methods to determine dominance. Many of the remaining historical articles discuss the concept, methods, and terminology, whereas newer work explores the underlying mechanisms of eye dominance. This section synthesizes and analyzes the literature on eye dominance in vision science and outside HCI, structured according to our analysis framework for vision science articles.

2.3.1 Eye Dominance Definition

Eye dominance is defined differently across the selected articles from vision science and is viewed from multiple perspectives. We inductively categorized the definitions of our sample thematically into five classes: preference, task dependency, superiority, laterality, testing method, and dominance type. Table 2.5 shows these classes and their prevalence. The classes are not mutually exclusive, as a single definition may fall into multiple categories. As a result, the of sum all category counts of eye dominance definitions exceeds the number of articles analyzed.

Various terms are used to describe eye dominance. The most frequently used terms are ocular dominance [71], eye dominance [146], sighting dominance [24], sighting eye [22] or motor dominance [149], all describing a phenomenon in which one eye presents a dominant or superior behavior to the other. Furthermore, there are various approaches to defining the concept of eye dominance.

2.3.1.1 Preference

48 articles describe sighting dominance as a "preference"; "Ocular dominance is the preference of one eye over the other in terms of sighting, sensory and oculomotor tasks" [102]. The term "favoring" is sometimes used similarly to "preference". Such

Table 2.5: Classification of eye dominance definitions

Classes	Description	N
Preference	"Preference of one eye over the other" [91]	46
Task Dependency	"...for tasks in which both eyes cannot be used simultaneously, as when looking through a telescope" [20]	33
Superiority, Direction or Control	"...the faculty which one of the eyes commonly exercises of leading or dominating the other, both in fixation and in attentive or perceptive function" [67]	19
Laterality	"Functional laterality is observed in paired organs of the body such as the hands, legs, and cerebral hemispheres. The presence of the dominant eye is also known" [50]	15
Testing Method	"Eye dominance is defined as simply the results obtained from these tests" [89]	11
Eye Dominance Types	"...ocular dominance is a multifaceted phenomenon... we must first specify which type of dominance is being referred to: sighting, sensory or acuity dominance" [22]	9

Note: Classes are not mutually exclusive.

an example is a definition by Coren, "Sighting eye, whose input is favored" [22]. However, the use of the terms "preference" or "favoring" can be misleading; it implies that eye dominance is a conscious choice, which is uncertain. One definition of eye dominance describes it as an "inherited tendency" [65], suggesting that it is not a result of other factors. This perspective of eye dominance reflects a difference in how the eyes process input, which seems to be a key element and is reflected throughout all classes.

2.3.1.2 Task Dependency

A total of 34 articles present their definitions of eye dominance within the task context, often being "monocular viewing conditions" [14]. In this theme, sighting dominance is defined as the eye that is "chosen" or "dominates" during a specified task. These specified tasks are commonly "aligning a telescope" or "looking through a keyhole" [121, 21, 84, 97]. Hence, the dominant eye is the eye used in the described situations. Thus, sighting dominance is explained to appear in situations when both eyes cannot be used simultaneously [145]. Lund explains sighting dominance as the "dominance of eye in visually directed movements" [77]. In these movements, such as reaching, grasping, and pointing, the choice between the two eyes has to be made, whether conscious or subconscious [102]. One definition acknowledges the dynamic nature of eye dominance; "Dominance can change and may switch between the eyes depending on the task and physical condition of the subjects" [122]. Nevertheless, this, too, highlights the task as a strong determinant of eye dominance.

2.3.1.3 Superiority, Direction or Control

In 19 articles, the dominant sighting eye is attributed to superior, dominant, or controlling over the non-dominant eye in specific tasks or activities. For example, Lund explains "ocular dominance, or the tendency of one eye to become the directing and controlling eye..." [76]. In this context, directing or controlling can be understood similarly to the previous class of "preference", implying the subconsciousness of this behavior. This class, unlike preference, includes an added dimension: a behavioral component, which demonstrates superior effects for the dominant eye compared to the non-dominant eye. For example, Clark explains the "dominance" factor of the dominant eye as "greater use" and "greater sensitivity" [17]. Likewise, Foutch and Bassi state the dominant eye has better visual function than the non-dominant eye [36]. This dominance and control of one eye is explained to possibly result from the control of the dominant cortex [56], rather than conscious behavior. Furthermore, studies have recognized that the dominant eye influences perception and behavior beyond visual alignment tasks, as "subjects are more accurate, and images appear clearer, more stabilized and perhaps larger" [131]. Details on perceptual effects and higher functioning of the dominant eye will be discussed in Section 2.3.4.

2.3.1.4 Laterality

A sum of 15 articles compares eye dominance with other body or limb laterality, such as hand or foot. However, this comparison has been followed by the explanation that these preferences do not function similarly. For instance, Miles notes, "But as a matter of fact the functioning of the two motor coordination systems (hand and eye) are really not analogous. Picking up a needle requires just one hand and to use both for such a task would be very clumsy. The needle is, however, viewed with both eyes as you reach for it and, typically, is threaded on the basis of binocular impressions" [88]. Still, newer work refers to eye dominance as a "lateral preference" [159]. Akabalieva et al. explain lateralization as "the preferred localization of a function or activity on one side of the body", eye preference being an aspect of this "functional lateralization" [1]. Yet in this context, Laby distinguishes the eyes from the limbs, as the eyes are receptor organs, which are not lateralized in the brain [68]. Overall, laterality serves as a general term to categorize eye dominance and draw comparisons to other forms of body lateralization in definitions.

2.3.1.5 Testing Method

Eleven articles described eye dominance in the context of the testing method used to determine the dominant eye. Authors often highlight the dependence of eye dominance on the testing method used, such as the binocular alignment task [24]. Zeri et al. refer to the "multiple dimensions" of eye dominance, as the results obtained in one test may not correlate with those of another method [160]. Some definitions of eye dominance limit these to the result of a specific testing method

(e.g., "It is determined classically based on the hole-in-the-card test" [139]).

2.3.1.6 Eye Dominance Types

Nine definitions distinguish between different types of eye dominance. Most commonly, these are sighting-, acuity-, and sensory dominance, as first named by Coren & Kaplan [22]. However, other studies mention motor-dominance or ocular prevalence as additional eye dominance types. When contrasting these types, authors highlight the diversity in functionality, "rivalry-dominance, which is purely sensory, and sighting dominance, which is motor in character" [126]. Some definitions differentiate between the various types within their explanation of eye dominance, whichever is most relevant to their work. Nevertheless, sighting dominance is ascribed as "The most significant, consistent, reliable, and important type" [110, 109].

2.3.1.7 Summary

The analysis of the eye dominance definitions within Vision Science shows that "eye dominance" encompasses a rather broad concept. Eye dominance generally refers to a visual behavior associated with sighting, emphasizing the differences in visual processing between the two eyes. The specific task used can influence which eye is dominant, typically resulting in superior perceptual performance. Moreover, eye dominance is distinct from other forms of bodily or limb laterality. It also varies depending on the testing method employed. Vision science differentiates between multiple types of eye dominance, underscoring the complexity of this phenomenon. Thus, more specific terminology is required when referencing the behavioral phenomenon. An example would be to specify the type of eye dominance used (e.g., sighting-, acuity-, sensory dominance) and refer to it as "dominance" rather than a "preference". The widespread understanding is that the sighting (dominant) eye is typically involved in situations that require alignment of objects varying in depth, such as pointing and grasping. In summary, the dissimilarity of the dominant to the non-dominant eye is highlighted among all definition approaches. Since eye dominance lacks a single, definitive description, Section 2.5.1.1 offers additional recommendations.

2.3.2 Eye Dominance Testing Methods

Many methods measure or determine the dominant eye, yet these differ greatly in task, complexity, and outcome. Table 2.6 provides an overview of the main methods used to determine sighting dominance and the varied parameters between studies. Some articles utilize more than one testing procedure.

The most commonly utilized methods are the hole-in-card test (Dolman test), the Porta test (pointing test, near-far-alignment test), the Miles test (ABC test), and testing using a special device or apparatus. Other tests with different names are

Table 2.6: Overview of frequent methods used to determine sighting eye dominance

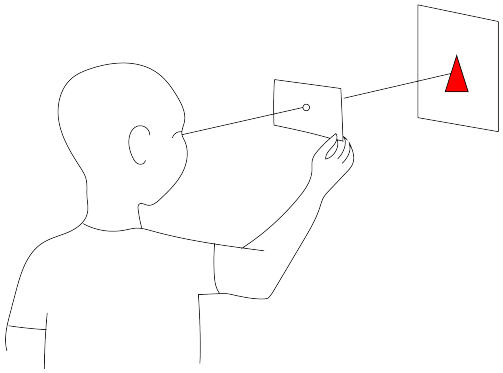
Method	Procedure	Parameter Variation	N
Hole-in-card, Dolman-Test (Figure 2.3a)	Subject views a distant target through a hole in a card or board held in front of them. Subjects alternately close one eye. The eye that still sees the target through the hole is labeled dominant [1].	Hole size, card/board size, target distance, target size, card/board movement or non-movement	36
Porta-, Pointing-, Near-and-far Alignment Test (Figure 2.3b)	Alignment of a near and a distant object or target in front of the subject. Commonly, one eye is closed, followed by the other. The open eye with which the two objects remain aligned is noted to be dominant [71].	Objects/targets used to align, target distances, hand or finger used	27
Miles-, ABC-Test (Figure 2.3c)	The participant views a card or target through a cone ("V-Scope"). They are instructed to indicate what they see on the card while the experimenter notes which eye they are aligning the cone with [88].	V-Scope or vision tube, testing distance, target	14
Apparatus Testing	Test conducted using a specially constructed device/apparatus such as the monoptometer [77].	Subject task (e.g., aligning two stimuli), wearing of filter goggles	11
Other Method	e.g., Questionnaire	—	12

Note: Methods are not applied mutually exclusively.

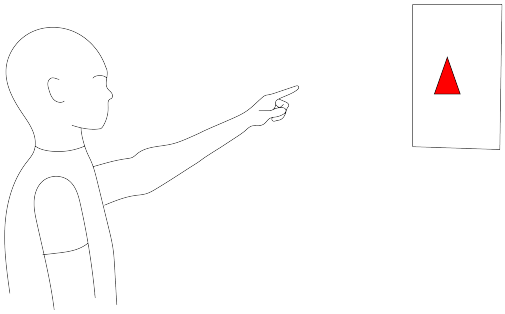
also applied, yet they can generally be categorized into the previously mentioned primary methods, which can vary in their parameters and execution. Studies often repeat a procedure multiple times or use more than one method when testing eye dominance [11, 24, 111, 125]. Given the nature of these testing methods, sighting eye dominance is measured in monocular situations, requiring a conscious or subconscious choice between the two eyes [17]. The following section summarizes the main methods, describing the general procedure, the parameters that vary between studies, and the main differences between the tests.

2.3.2.1 Hole-in-card Test

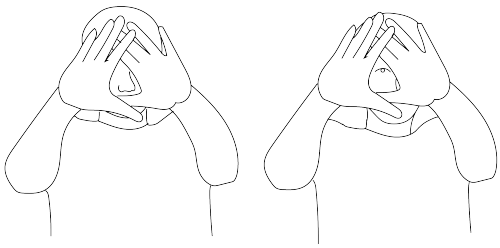
The Dolman-, also known as the "Hole-in-card Test", was employed in 36 studies to determine sighting eye dominance (cf. Figure 2.3a). The general procedure follows: A subject views a distant target with both eyes open. A card or board containing a hole in the center is held before the subject. The task is to view the target through the hole while keeping both eyes open. The subject alternates the closing of one eye. The open eye, with which the subject can still see the target through the hole, is dominant. A test named "Asher-test" greatly resembles the hole-in-card test procedure. However, instead of using a card with a hole, the participant



(a) Hole-in-card test. Participant views a distant target through a card and alternately closes each eye; the eye whose closure disrupts alignment is dominant.



(b) Porta test. Participant points at a distant target and alternately closes each eye; the eye whose closure shifts alignment is dominant.



(c) Miles ABC Test. Participant looks through a hand-formed opening; the aligned eye is identified as dominant (right).

Figure 2.3: Various eye dominance tests.

extends their open hands, thumbs extended, in front of themselves. The two hands are aligned above each other until a small hole forms between thumbs and index fingers [19]. The participant then uses this hand formation instead of the card. Parameters of these methods vary from study to study. For example, the hole size in the card can be 0.5 inches (1.27 cm) [123] or "pencil-sized" [113]. Nevertheless, the general procedure affords a hole large enough to view a target yet small enough to ensure the participant cannot use both eyes for this viewing task. Similarly, the size of the card or paper can range from 15.5 x 15.5 inches (39.37 x 39.37 cm) [113] to 30 x 30 cm [42]. Essentially, the high variability of the card dimensions implies a subordinate role in the classification procedure, provided that the card is comfortable for participants to hold. Since subjects usually hold the card themselves, the distance from the eyes can differ between participants due to individual arm lengths and personal comfort levels [34, 1]. Scheidemann indicates a card distance range of 15 to 20 inches (38.1 - 50.8 cm) from the participants' faces [123]. The distant target

that is viewed through the hole is placed at a farther distance than the card. These can range from 2.5 meter [36], to 4 meter [52] up to 20 feet (6 meter) [134, 34]. No matter the distance of these targets, their dimensions remain relatively small. Fink describes the distant target as a "small point of light" [34]. However, judging by the distance from the participant (6 meters), it can be assumed that the target was sufficiently large to remain visible at such a distance. A study may use a 2 [36] to 5cm diameter circular target [132]. In most procedures, participants must hold the card using both hands [1, 102, 107]. This ensures that the hand used does not influence the results.

2.3.2.2 Near-far-alignment Test

A near-far-alignment test was used in 27 studies (cf. Figure 2.3b). This test, also known as the Porta- or point test and sometimes called the Rosenbach test, involves aligning a near and distant target. The near target may be the subject's own finger or another closer target placed in front of a distant target. Similar to the hole-in-card test, one eye is closed. The eye with which the subject perceives the two targets remaining aligned is labeled as dominant. In contrast to the hole-in-card test, where the card occludes the surroundings, the finger or close target here is to align with the distant target. The objects that are used for this alignment can be either a finger ([13]), a pencil ([28]), a ruler ([11]), or other smaller objects. This task set-up commonly requires participants only to use a single hand to either point or hold up the object needed for alignment [28]. To account for a possible hand bias, the test may be repeated with both hands [109], or both hands may be used simultaneously throughout the test [11]. The precise location of the distant target is rarely discussed and is referred to as a "distant object" [1].

2.3.2.3 Miles Test

A total of 14 studies described the Miles test. The original Miles-test, also referred to as the A-B-C test, involves the use of a cone or "V-Scope", typically made by folding a piece of paper, which is then pressed open to create a funnel that is only large enough for one eye to look through [154]. Participants are instructed to view a distant card through the cone they hold with both hands. The card, held by the experimenter at a distance from participants, shows two discs differing in darkness. The participants are required to indicate which of the two discs is darker. While viewing the card through the cone, participants subconsciously align the cone with either eye [88]. The experimenter notes which eye the cone is aligned with, as seen in Figure 2.3c. This method enables eye dominance testing without participants being aware of what is being tested. The task participants must do is a decoy, only assuring they are looking at the experimenter through the cone. Some of the parameters used in the study vary. For example, testing or target distance can range from 2 meters [112] to 15 feet (4.57 meters) [91]. Furthermore, many procedures substitute the V-scope or paper cone with a hand-based method,

in which participants stack their hands, creating a viewing hole between both index fingers and thumbs, as seen in Figure 2.3c.

2.3.2.4 Apparatus Testing

Eleven articles report an eye dominance test using an apparatus. When testing for other dominance types, acuity or sensory dominance, devices or unique apparatuses are custom. However, some approaches testing for sighting eye dominance also use specially constructed devices. These studies using an apparatus to measure or determine the dominant eye were published between 1932 and 2005. However, contemporary work rarely considers testing eye dominance using apparatuses. When using an apparatus, the common task is the alignment of stimuli, "the subject... may be instructed to bring the circle into line with the fixation disk" [77]. In some instances, both eyes are kept open. Other approaches repeat their procedure monocularly with each eye, "Subjects were instructed to bring the lower (front) rod into line with the upper (back) rod by moving the handles with both hands. This task was performed with both eyes first, then with only the left eye (balanced right), with both eyes again, and finally with the right (left) eye" [100]. Often, any test involving some apparatus seems to test an aspect of eye dominance in combination with binocular fusion or sensory dominance, as discrepant stimuli are presented to both eyes simultaneously.

2.3.2.5 Other Methods

Twelve studies used alternative methods for determining the dominant eye, such as questionnaires in which subjects indicate the behavior they typically adopt in given situations. For instance, one item might be, "If you had to look into a dark bottle to see how full it was, which eye would you use?" [121]. However, this approach is limited due to its high susceptibility to inaccurate indications. Hence, immediate testing may be more reliable, such as a performance measurement "in which there were three items for eye sighting, such as: looking through a narrow opening into a dark bottle, looking through a keyhole, looking down a monocular microscope" [41].

The general qualitative and binary nature of eye dominance testing is critiqued, "All standard tests estimate dominant eye qualitatively, showing only left or right dominance. Assessment should be done quantitatively, evaluating the degree of dominance." [97]. Yet investigations on "degrees of dominance" are scarce. Ho et al. measured eye dominance using a continuous scale of dominance [48]. This was achieved during a binocular alignment judgment task. Participants had to point at a cross in the center of a horizontal alignment chart with both eyes open. In turn, one eye was covered. During monocular sighting, participants were required to indicate which number on the chart their index finger was now aligned with. By adding the two numbers, a dominance score was determined.

2.3.2.6 Distinctions Between Tests

The various testing methods for eye dominance can be distinguished by three main factors: hand use, means of reporting, and participant awareness.

2.3.2.6.1 Hand use: The different approaches to hole-in-card or near-far-alignment tests all encompass the alignment of one near object (finger, card, or tube) with one distant object in front of the subject [131, 113]. These methods require the subject to pursue alignment either with both [1] or one hand [113]. Using hands during the alignment process can be eliminated when testing eye dominance with apparatuses, as the device is used to align two objects [100]. Instead, the hands are used to manipulate the device, aligning the objects, and no longer in a hand-eye coordinative manner. Excluding single hand-eye coordination during testing prevents a possible handedness bias and thus a distortion of testing results [12].

2.3.2.6.2 Means of reporting: Within any testing method, the result can be reported either by the experimenter ([22, 37]) or the subject ([38]). In subject reporting, the participant must indicate whenever a shift or misalignment of two targets at differing depths occurs. In this instance, the experimenter relies entirely on the subjects' reporting. A key limitation of this approach is the tendency to bias or inaccuracies. The experimenters themselves are unable to determine the dominant eye of the subject. Experimenter reporting affords a different testing setup. In such cases, the experimenter must be able to determine the dominant eye, e.g., by standing in front of the subject, with a direct view of both of their eyes. The subject is then instructed to point directly at the experimenter's nose. Ideally, one of the subject's eyes will be aligned with and ultimately occluded by their pointing finger. Thus, the experimenter can report the subjects' dominant eye.

2.3.2.6.3 Participant Awareness: As seen in the Miles-test procedure, this method can be conducted without the participant knowing the true testing purpose [154]. By looking at a card the experimenter holds, the participant subconsciously aligns the cone with one of their eyes, which the experimenter notes. The task given to the subject in the Miles test, indicating which of the two shapes on the card is darker, hides the true purpose of the test. As Miles states, "It may be repeated many times on the same patient with little interference from handedness and avoids the automatic informing of the patient in regard to findings." [88]. However, it remains unclear whether awareness of the testing purpose may interfere with the results.

2.3.2.7 Testing Reliability & Consistency

The hole-in-card test proved a high test-retest reliability [125]. Similarly, Ho et al. demonstrated excellent test-retest reliability for a variation of a distance-pointing (Porta) sighting dominance test [48]. However, once the target distance was varied

(40-50 cm vs. 400 cm) in a hole-in-card test procedure, results differed [52]. Similarly, the results of two tests may disagree, although they seemingly test the same phenomenon. A frequent concern across most methods is the inconsitencies of results, both within a test and between different tests. Ultimately, test and re-test results tend to differ, and different tests produce different results. Clark and Warren claim, "The lack of agreement [of test results] may be an indication [...] that ocular dominance is not a general, unitary factor; that it is specific to the method of measurement, and to the situation in which the test is made." [17]. From this, it can be concluded that the best practice is to adhere to a consistent method and set of parameters within a study for reliable and consistent eye dominance testing results and replicability. Refer to Section 2.5.1.1 for further recommendations on eye dominance testing methods and procedures.

2.3.2.8 Summary

Overall, there is no standard testing procedure for eye dominance. Many testing procedures have similar features yet distinct names. While the main parameters may vary between these, the general nature of the task remains the same: alignment at a central viewing angle. All rely on establishing the line of vision, where a target and often a middle reference point are aligned with the eye. One line of vision should be closer aligned with the target than the other. However, when selecting a method for testing eye dominance, it is essential to rely on one that offers high replicability, reliability, and impartiality. This involves maintaining consistent procedures and parameters when repeating a study. The hole-in-card method and the near-far alignment test are the most frequently utilized and dependable techniques for assessing eye dominance. We further address this in Chapter 4.

2.3.3 Factors Influencing Eye Dominance

An inductive approach was applied to identify factors that might influence sighting dominance. These included hand preference, body laterality, gender, heritability, eye conditions, horizontal viewing angle, viewing distance, and hand used during motor movement. Each of these are categorized into individual or contextual factors. We consider individual factors such, that determine or potentially predict an individual's eye dominance as a personal and intrinsic characteristic. These include hand preference, body laterality, gender, heritability, and eye conditions as potential individual factors influencing individual eye dominance, as shown in Table 2.7. A contextual factor is an external condition that can influence eye dominance behavior in a given context. We identified horizontal viewing angle, viewing distance, and hand used during motor movement as contextual factors. Overall, the dominance of the right eye is claimed to be observed more frequently (70% right-eyed) [107].

Table 2.7: Overview of individual and contextual factors influencing sighting dominance behavior

Factor	Description	Determining Factor	
		Supporting Studies	**Non-Supporting Studies**
Individual Factors			
Hand Preference	"There was a highly significant relation between handedness and eyedness" [13]	7	2
Body Laterality	Correlation between dominant side and dominant eye [34]	1	2
Gender	"We found no convincing evidence for sex differences in either the incidence of left-eyedness" [12]	1	2
Heritability	"There is a significant correlation between the laterality (eye preference) of parents and children" [121]	2	0
Contextual Factors			
Horizontal Viewing Angle	"Our main finding is that ocular dominance reverses as a function of horizontal gaze angle" [58]	3	0
Viewing Distance	"Four subjects switched dominance between far and near assessment" [52]	2	2
Hand Used During Motor Movement	"We also found that sighting dominance thresholds change predictably with the hand used" [14]	2	1

Note: Classes are not mutually exclusive.

2.3.3.1 Individual Factors

Hand preference and eye dominance show a correlation. Nine studies investigating whether hand preference tends to align with the dominant eye have shown an association with minor disagreement [37, 13, 42, 19, 102, 12, 40, 3, 110]. Within this context, hand preference refers to the dominant or favored hand of the individual in tasks that allow hand use.

One study reported little relationship between handedness and ocular dominance in 24 subjects (aged 20 to 61) [37]. Eye dominance was tested with a simple hole-in-card test, yet the handedness testing procedure was not further mentioned. In two further studies, however, the association between handedness and sighting dominance has been observed in males only [42, 110]. With sample sizes of 200 (aged 18 to 55) [42] and 160 (ages not reported) [110], both studies employed detailed, multi-item handedness questionnaires and 3 eye dominance tests to assess

participants. Similarly, Combs found a relationship between hand and eye preference when combining data of males and females [19]. This study involved 143 participants (aged 18 to 40 years), handedness was based on the preferred hand for writing, and eye dominance was assessed using the "Asher" method. In their study of 50 students (aged 17 to 22), Gronwall and Sampson [40] used multiple eye dominance tests alongside a handedness questionnaire but found no correlation between the two. The most recent work refers to a frequent, yet not absolute, display of a dominant-hand and dominant-eye correlation, "The dominant eye is often, but not always, on the same side as the master hand" [102]. These results are based on data from 45 healthy middle-aged participants, assessed using the hole-in-card test; handedness testing was not reported.

In a meta-analysis of 686 studies, Bryden observed a significant relationship between handedness and eyedness, showing 72.9% of the right-handed subjects testing as right-eye dominant [13]. A later meta-analysis of 54 datasets comprising 54,087 participants confirmed a general association between handedness and eye dominance [12]. However, the nature of this relationship remains unclear, as some eye dominance measures may be unintentionally biased by the participant's hand preference during testing. This underscores the problem of non-standardized procedures for assessing both handedness and eye dominance.

Analyzing trends across populations in eye dominance remains difficult due to the high prevalence of right-handedness and right-eye dominance. This natural skew can make it challenging to observe or generalize findings across less common combinations (e.g., left-handed with left-eye dominance or mixed dominance profiles). While many studies report a tendency for hand preference and eye dominance to align, we interpret this as a general association rather than a predictive relationship. We do not consider hand preference to be a reliable predictor of eye dominance.

It is debatable whether body laterality, described as limb preference, determines eye dominance. Three studies mention a possible relation [100, 4, 34]. The limb's preference extends beyond the hand to the entire body and different limbs. The typical procedure for limb preference involves tests such as questionnaires [100] or observations during practical tasks, e.g., when kicking or throwing a ball [4]. One article argues high agreement between the dominant side and the dominant eyes in individuals [34]. Similarly, Annett observed a connection between eye dominance and footedness in 805 subjects, with eye dominance tested using a variation of the hole-in-card test [4]. However, another study with 612 subjects found no significant correlation between the dominant side and the dominant eye, though it excluded left-handed individuals [100]. In this study, the dominant side was determined through a binaural hearing test for ear dominance and a variation of Porta's alignment test using a special apparatus to assess the dominant eye.

Due to the limited number of studies and the complexity of body laterality—with numerous body parts and a wide range of individual variations—it is difficult to

identify or generalize consistent associations. Additionally, selection bias, such as the exclusion of left-handed individuals and the overall higher prevalence of right-handers in the population, significantly affects how the results can be interpreted. While individual patterns of association may exist, as seen with handedness in the previous section, these should not be considered reliable predictors.

Three studies contribute to research investigating the relationship between eye dominance and gender [12, 42, 19]. Two studies found no evidence of gender differences in the prevalence of left-eyedness [12]. However, one study found a relation between handedness and eye dominance in males only [42]. This was not seen in females, where the incidence of right eye dominance remained higher, independent of hand preference. Yet again, no such relationship was found in other work. The relationship between eye and hand preference was observed to be significant, regardless of gender [19]. However, as addressed previously, gender-related differences became apparent when eye dominance was considered alongside other factors like handedness.

Two studies explored the possible heritability of eye dominance. The results of family data analysis indicate the heritability of eye dominance [12, 121]. A significant correlation was observed between the dominant eye of parents and children. Reiss mentions, "the frequency of individuals with left-eyedness increases continuously with the number of left-eyed parents, and there is no evidence of assortative mating" [121]. Furthermore, Bourassa assumes that eye dominance does not result from cultural pressures [12]. Evidence on the heritability of eye dominance indicates a correlation, suggesting a genetic component as it appears in patterns within families.

2.3.3.2 Contextual Factors

Ten studies investigate contextual factors of eye dominance. The three main contextual factors discussed are viewing distance, viewing angle, and the hand used in motor movement while testing for eye dominance. Contrary to individual factors explored in the previous section, contextual factors are external conditions that influence participants' eye dominance behavior. The listed contextual factors support the concept of eye dominance as dynamic and can reverse within subjects, depending on the context.

Khan and Crawford were the first to demonstrate how the horizontal viewing angle reverses eye dominance [58, 61]. In their work, the participants switched eye dominance on average 5°off-center. Banks et al. further explained this behavioral aspect resulting in relative retinal image size rather than eye position [8]. Most, if not all, methods for testing eye dominance are conducted at central viewing angles. This could explain why the dynamic behavior often goes unnoticed. The left eye tends to dominate the left-outermost horizontal viewing field, as the nose typically occludes the view from the right eye and vice versa. However, it is rarely

considered in studies. Nevertheless, these findings highlight eye dominance may change temporarily, depending on where a participant looks.

Findings from four studies on viewing distance as a factor inducing a change in eye dominance remain inconclusive [34, 27, 52, 48]. One paper noted, "Ocular dominancy does not shift when the focus is changed from distant to near vision" [34]. Similarly, Crider states that the distance of the fixation object is unrelated to the dominant eye [27]. In newer work, however, Johansson et al. observed a switch in some participants' eye dominance between near and far testing distances when using the hole-in-card procedure [52]. Furthermore, a greater viewing distance results in a greater magnitude of sighting dominance, as demonstrated in recent work [48]. This was measured using a simple alignment task: participants pointed at a target and alternately closed each eye. The visual displacement between the fingertip and the target indicated how strong the eye dominance was. At greater testing distances, the visual displacement increased, indicating a greater magnitude of sighting dominance and thus challenging the notion that eye dominance is a binary concept.

The influence of greater depth on eye dominance may be too subtle to detect on a binary scale, so a method similar to Ho et al.'s, locating eye dominance on a continuous scale, is required [48]. Hence, considering distance as a variable when testing for eye dominance could be relevant.

Finally, three studies investigated a possible dependence of eye dominance on the hand used during a motor movement for classification or pointing, with two reporting a positive association and one finding no strong support for this relationship [14, 58, 27]. The hand used during reach-and-grasp or pointing tasks is independent of the preferred hand, as discussed previously as an individual factor (cf. Section 2.3.3.1).

When testing for eye dominance twice in a modified Miles test, once with the left and once with the right hand, a change in eye preference was seen in only 15 of 717 participants [27]. In contrast, Carey notes, "using the hand ipsilateral to the dominant eye led to a switch in eye dominance further from midline compared to using the hand contralateral to the dominant eye", while testing using the Porta and Miles test [14]. This pattern was also observed in work by Khan and Crawford, where "the choice of hand had a moderate but consistent effect on the dominance transition curve" when using a modification of the hole-in-card test [58]. A possible explanation is that the effect results from optimizing vision during a motor movement. That said, the hand used during a motor movement may influence or bias which eye is dominant. This effect would be particularly pronounced in hand-eye coordination tasks and should be carefully considered.

2.3.3.3 Summary

The results on the individual factors that influence sighting dominance are varied. Some studies report associations between the observed factors, hand preference, body laterality, gender, heritability, and eye conditions, while others reject a

relationship. There is no consensus on specific factors that might influence or prove the relation to sighting dominance but strong evidence for hand preference and heritability. Consequently, the individual factors cannot provide a definitive and reliable prediction of eye dominance, yet can be considered when interpreting results or designing with eye dominance. Contextual factors refer to influences on eye dominance within the individual. Results indicate that horizontal viewing angle and the hand used during a hand-eye coordinated motor movement temporarily influence eye dominance behavior within individuals.

2.3.4 Eye Dominance Effects

Eye dominance changes or leads to differences in behavior or performance between the dominant and non-dominant eye [131, 89]. With that, it has been shown to affect egocentric localisation and posture [10], perception [111], visual processing [122], and hand-eye coordination [76].

2.3.4.1 Egocentric Localization & Posture

Eye dominance demonstrated an effect on egocentric localization and posture in six studies [9, 108, 126, 38, 113, 96]. Some indicate that the perceived center of the body (egocentric localization) is shifted towards the dominant eye [9, 112, 126]. Even under monocular viewing conditions, the egocentric localization was biased towards the side of the dominant sighting eye [112, 126]. Consequently, eye dominance has been shown to influence posture. A head tilt towards the dominant eye was observed, shifting the dominant eye more towards the body midline, "Thus a right-eyed S tends to carry his head to the left and a left-eyed S tends to carry his head to the right, and Ss with ambiguous eye-dominance tend not to manifest any consistent head-tilt" [38]. Participants of another study have also been shown to align their dominant eye more centrally in their field of vision, "The results showed that eye dominance and ipsilateral head rotation were significant in both groups. These findings suggest a strong tendency for dominant eye to rotate the head to the ipsilateral side" [113]. However, other work persists on the "cyclopean-eye hypothesis," reflecting that the perceived egocenter is located on the midline between the eyes [96].

2.3.4.2 Perception

Six studies demonstrated a difference in perception between the dominant and non-dominant eye [23, 109, 111, 36, 65, 131]. Some results indicate that objects are perceived to be larger and sharper with the dominant eye [23, 109]. A stabilized image remains in view longer with the dominant eye than the non-dominant eye [111]. One study demonstrated a greater contrast sensitivity in the dominant eye, "contrast thresholds were significantly lower for the dominant than non-dominant eye" [36]. Similarly, the dominant eye shows higher performance in colour vision discrimination, specifically "attributed to higher sensitivity of the r/g local colour

spectral region" [65]. Other studies indicate a higher performance of the dominant eye during various perceptual tasks, such as detecting "the odd element" during visual search [131]. Overall, these findings suggest a superior perceptual performance of the dominant eye.

2.3.4.3 Visual Processing

Twelve studies have demonstrated an impact of eye dominance on visual processing [122, 56, 24, 89, 50, 46, 138, 66, 139, 43, 94, 27]. When viewing and responding to a flash stimulus, binocular vision outperforms monocular vision. However, under monocular conditions, reaction times are quicker with the dominant eye compared to the non-dominant eye [89]. Moreover, the dominant eye showed shorter visual latency, indicating faster processing than the non-dominant eye [24, 138].

Eye dominance also influences the latency of saccades based on the visual direction. For example, left-dominant eyes tend to have shorter latencies for leftward saccades compared to rightward ones [66]. Furthermore, stronger eye dominance leads to more accurate saccades towards targets in the visual field opposite the dominant eye [139]. The dominant eye shows faster horizontal saccadic velocities than the non-dominant eye, but no significant differences are found in smooth pursuit or vertical saccades [131]. Independent of reaction time to a visual stimulus, the dominant sighting eye moves differently than the non-dominant eye. For instance, Oishi et al. observed a higher velocity of the dominant eye in horizontal saccades [94]. While there are no consistent differences in latency or time constants of vergence movements, the amplitude and gain of accommodative vergence vary depending on which eye is leading the movement [43]. In dynamic visual tasks, the dominant eye exhibits higher peak velocities and faster movement during the initial phase of visual fusion. In contrast, both eyes perform equally during the sustaining phase [56]. Regarding switching focus, dominant eyes have longer response times for near to far but are faster for switching from far to near. Also, the velocity for near-to-far changes is slower, while far-to-near changes are quicker in dominant eyes, especially when both eyes are used [50].

Other study results show "perceptual accuracy was found to be significantly higher when viewing with the dominant eye, both when stimulus arrays were briefly presented and scanned, and when scanning was restricted to the post-exposure period" [91]. Additionally, the dominant eye is better able to focus on near objects than non-dominant eyes, evidenced by a greater near point of accommodation [122]. However, visual acuity is assumed not to be related to eye dominance [27]. Although the differences in reaction and response times between dominant and non-dominant eyes are not statistically significant, eye dominance tends to affect the size and type of eye movements, with the non-dominant eye showing larger movements during monocular accommodation [46]. Furthermore, motion coherence was higher whenever signal dots were presented to the dominant right eye [74].

2.3.4.4 Hand-eye coordination

In the context of hand-eye coordination, when pointing or aiming rapidly, binocular trials outperform monocular trials. However, during monocular trials, the dominant eye demonstrated better and more accurate scores in two studies [76, 91]. Nevertheless, the method for detecting the dominant eye in this study used only the dominant hand. It is unclear whether this effect remains when using the non-dominant hand.

2.3.4.5 Summary

The effects on egocentric location and posture, perception, visual processing, and hand-eye coordination demonstrate the influence of eye dominance on human behavior. However, each individual finding appears to have been confirmed in single studies only. More nuanced patterns may be overlooked, and inconsistencies—such as those observed in studies on factors influencing eye dominance—are less likely to emerge. Nevertheless, these findings collectively highlight the multifaceted nature of eye dominance. More comprehensive research is required to understand the broader implications of eye dominance better and to identify how it can be effectively leveraged.

2.3.5 Relation of Eye Dominance Types

As mentioned in Section 2.3.1.6, different types of eye dominance are frequently recognized and referenced in literature, "There are at least two kinds of ocular dominance, one of which has a motor character and expresses itself in monocular sighting preference but is independent of the brainedness laterality which governs handedness" [149]. The most often described eye dominance types are referred to as sighting, acuity, and sensory dominance. The findings in studies on whether the different types are interconnected are inconclusive. For instance, Lopes-Ferreira et al. observed an agreement in 72.7% cases when testing sensory and sighting dominance using a hole-in-card test [75]. However, in a different study, only 33.3% participants showed consistency between sighting and sensory dominance results, tested using the Miles test and rivalry tests [154]. Schoen and Wallace report eye dominance is not caused by basic processes in the eyes (retinal events) but instead results from a complex and dynamic interactional process of multiple cognitive and visual systems [127]. Pointer reports a statistically significant association between better visual acuity (acuity dominance) and sighting dominance in only two instances [106]. However, this review primarily focused on sighting dominance, and selection bias may have limited the ability to draw definitive conclusions. Nevertheless, the different types of eye dominance exhibit distinct behaviors, and depending on the application, it is important to carefully consider which type is most relevant or whether an interaction between types may occur.

2.3.6 Summary and key findings of vision science and eye dominance

Eye dominance has been a longstanding and well-researched topic in vision science. Its broad scope and various definitions indicate the complexity of the subject. It is known to be multifaceted and presents a dissimilarity in visual processing between the eyes. There is no standard testing procedure, and methods and results can vary depending on hand use, reporting means, and participant awareness of the testing purpose. Nevertheless, the hole-in-card test is noted as the most widely used and reliable procedure for determining the dominant eye. There is no conclusive consensus on which factors, if any at all, influence eye dominance, though there are strong indications pointing to certain influences. Findings of hand preference and heritability as individual factors suggest a possible correlation to the eye dominance behavior of individuals. In turn, contextual factors such as horizontal viewing angle and the hand used during motor movements have been shown to temporarily influence eye dominance in individuals, showcasing it as a dynamic and adaptable nature. Vision science also shows that the influence of eye dominance extends beyond sighting, affecting egocentric location, posture, perception, visual processing, and hand-eye coordination—all of which are relevant to HCI and the design of user-centered technologies.

2.4 Eye Dominance within HCI

This section synthesizes and analyzes the implementation and considerations of eye dominance in 52 HCI studies. We first provide an overview of how eye dominance is generally understood, recognized, and tested in the HCI field. Analyzing the motivation for implementing eye dominance in HCI work highlights the concept's relevance. Finally, we synthesize the results from implementing eye dominance in HCI to provide guidelines for implementing or considering eye dominance in future work.

2.4.1 Understanding Eye Dominance in HCI

The understanding of eye dominance within HCI according to different definition categories is shown in Table 2.8. HCI describes eye dominance from a similar lens as vision science, viewing it in terms of preference, subconsciousness, task dependency, body laterality, or the result of a perceptual effect, as definitions from vision science do. These perspectives are not mutually exclusive, and some definitions integrate elements from more than one.

A total of 16 articles explicitly define eye dominance. Of these, 10 studies define eye dominance as "preference" or "favoring" of one eye over another; "Humans have a preference for one eye over the other, referred to as eye dominance" [53]. As discussed in Section 2.3.1.1, these two terms may be misleading, as this may

Table 2.8: Frequency of definition categories for eye dominance

Definition	Description	N
Preference	"Humans have a preference for one eye over the other, referred to as eye dominance" [53]	10
Subconsciousness	"...it is taking place in the dominant eye's view field unconsciously" [90]	1
Task Dependency	"Preference of one eye over the other, when the target is straight ahead" [2]	3
Body Laterality	"Human laterality is the preference of humans to use one side of their bodies rather than the other" [136]	3
Perceptual Effect	Eye dominance is defined as a result of some perceptual effect, such as higher visual acuity in the dominant eye	3

Note: Classes are not mutually exclusive.

suggest an intentional choice between the two eyes. Only one study refers to eye dominance as a subconscious behavior, "...it is taking place in the dominant eye's view field unconsciously" [90]. Three articles acknowledge the task dependence of eye dominance [63, 64, 2]. From this perspective, eye dominance is a phenomenon occurring "in behavioral coordinates when only one eye can be used" [64]. Similarly, Akkil et al. define the task context of eye dominance further, limiting it to scenarios "...when the target is straight ahead" [2]. Another three articles compare eye dominance to other body laterality, such as handedness, "As most people have dominant hand, we also tend to have a dominant eye" [101]. Three studies reference a difference in perceptual effects between the two eyes, or superior characteristics to the dominant eye, "it often manifests physiological or refractive superiority over the non-dominant eye" [64]. In Vision Science, eye dominance is defined from multiple perspectives. However, the definitions from HCI work suggest that eye dominance is understood as a static attribute that is resistant to change. The distinction between the dominant and non-dominant eye is generally acknowledged; however, despite the complexity of eye dominance as a phenomenon, many articles (N=16) do not ground their work in theory or clearly specify which definition they adopt. The remaining studies do not engage with eye dominance definitions at all. The cited references are often older, suggesting a reliance on foundational studies, neglecting recent developments in vision science. For instance, relying on older studies limits our understanding of eye dominance in HCI, as more recent findings are missed. Newer work, however, recognizes eye dominance as a dynamic and context-dependent concept. For example, acknowledging behavioral differences, such as a higher contrast sensitivity of the dominant eye [36] could help design more visually optimized and user-tailored interfaces. This highlights a gap between the definitional precision in vision science and the pragmatic but sometimes vague usage in HCI. Addressing this will be essential for advancing more dynamic and context-aware applications, especially in emerging settings like real-world and virtual environments.

Table 2.9: Eye dominance testing methods in HCI work

Method	N
Report of testing for eye dominance	27
Description of eye dominance test used	22
Multiple tests within study	3
Hole-in-card Test	10
Miles Test	9
Porta Test	3
Unnamed[1]	3
Other[2]	2

Note: Methods are not mutually exclusive. [1] Unclear test description, e.g., "eye-dominance test" [120]. [2] Porn's or Rosenbach's test [150, 45].

2.4.2 Eye Dominance Testing in HCI

Within HCI, 27 studies report testing participants for eye dominance. Of these, 22 describe the testing method or indicate which test was used to determine the dominant eye. The remaining 7 only mention having tested eye dominance within their study, yet do not provide any further insights on the test used, or the procedure of determining eye dominance within participants. Table 2.9 shows the frequency of the different testing methods of eye dominance utilized within our corpus. Three studies indicate that each used two tests. Valkov et al. and Lee & Bae both indicated using the Porta and Dolman test [144]. Mayer et al. referenced the Miles and Porta test [82]. Zhang et al. indicate using multiple repetitions of the Miles-test [161].

A sum of ten articles reported conducting a hole-in-card test [156, 136, 143, 72, 54, 69, 31, 2, 64, 63], nine indicate using the Miles test [148, 93, 82, 32, 161, 86, 129, 2, 55], and three mention the Porta test [144, 72, 82]. Two studies indicate using the Porn's or Rosenbach test [150, 45]. Three studies do not name the exact test they utilized [120, 128, 141].

Many descriptions of eye dominance testing within the selected HCI articles are vague and lacking in description of the procedure and specific parameters used, such as the testing distance, e.g., "participants ... were asked to perform a Miles test (Miles, 1930) to determine ocular dominance" [148]. However, the implementation of the Miles test can vary from the original method. While the test was initially designed for an experimenter to observe which eye dominates, some researchers have modified this to resemble the hole-in-card method more closely. Instead of using a card, participants form a triangle using both of their hands, and while alternatingly closing one eye, report any perceived misalignment; "This test has been transformed in many ways, most popularly through the hole-in-card test. In our study, subjects form a triangle with their hands and focus a poster on a distant wall in the center. They then close one eye at a time and identify the eye through which they saw the most of the poster" [129]. Aside from naming the test, the parameters and

more precise procedures are not described any further, limiting the replicability, e.g. "simple thumb occlusion test" [141], "We determined the dominant eye of participants with the Miles test" [32].

Given the absence of a gold standard for the parameters of each eye dominance test, and considering insights from vision research regarding eye dominance (cf. Section 2.3.2.6 and Section 2.3.2.7), it becomes crucial to precisely describe all specifications and parameters to enable replication and optimize result interpretation. Assuming that eye dominance is static may lead to simplified testing procedures, as no changes are typically anticipated. However, the dominant eye can change (cf. Section 2.3.3), and established testing methods are constantly evolving, with stimuli, procedures, and metrics varying from study to study. These variations can include factors such as target distance, types of stimuli, or how the dominant eye is identified — whether by the subject or through the experimenter's observation. Providing a limited description of testing procedures and variables restricts the replicability of many studies, as also suggested by findings in vision science (cf. Section 2.3.2.7), and hampers generalization of results. Hence, we recommend the transparent reporting of target/testing distance, determination procedure of the dominant eye (participant or experimenter indicating), and which/how hands are used throughout the test. In conclusion, as highlighted in vision science (cf. Section 2.3.2.6), the hole-in-card procedure is not only a reliable method but also the most commonly employed technique in both vision science and HCI.

2.4.3 HCI Fields Considering Eye Dominance

To examine investigate the role of eye dominance in HCI, we analyze research areas that integrate it in their work. This allows us to outline the domains where eye dominance has been considered relevant, providing an overview of its perceived importance within the field. The articles' main themes are fundamental research on human factors (21), 3D user interfaces (17), energy optimization (8), and evaluation of viewing displays (6). The articles generally relate to visual technologies; hence, understanding the human visual system and its influence is a core factor. Table 2.10 overviews the main HCI fields considering eye dominance.

2.4.3.1 Research of Human Factors

One theme of incorporating eye dominance in HCI work is to provide fundamental research on human behavior and perception in context of visual technologies. A sum of 19 studies motivates their work from this aspect. These investigated behavioral aspects can be categorized into four subtopics: binocular rivalry/stereoscopic vision, pointing and gestures, depth perception, and vision and eye movement.

Eight articles specifically investigated binocular rivalry and stereoscopic vision [135, 151, 70, 161, 156, 150, 63, 101]. These works explored the perceptual effects of presenting different content to each eye on stereoscopic 3D displays. The

Table 2.10: HCI fields that consider eye dominance

Field	Description	N
Research of Human Factors		
Binocular Rivalry/Stereoscopic Vision	"... explore how we may present binocular image pairs that differ in other ways to create novel visual experience." [161]	8
Depth Perception	"We performed several basic evaluations... based on those factors that can change depth perception: binocular or monocular, viewing distance, eye dominance, ..." [158]	6
Pointing & Gestures	"The effects of eye dominance on pointing movement were also examined." [92]	3
Vision and Eye Movement	"Therefore, we experimentally investigated the amount of the displacement of the pupil center while the fixation point was changed transversally." [45]	4
3D User Interfaces		
Cursor Development and Content Placement	"We propose using a virtual cursor in the dominant eye and a reinforcing cursor in the non-dominant eye to avoid ambiguity problems ..." [47]	8
Distance Selection/Pointing	"... show that being in a virtual environment affects how users point at targets." [82]	6
Touch Input	"... analyze the relation between the 3D positions of stereoscopically rendered objects and the on-surface touch points, where users touch the surface." [144]	3
(Energy) Optimization	"...eye-dominance-guided foveated rendering (EFR), renders the scene at a lower foveation level (with higher detail) for the dominant eye than the non-dominant eye." [86]	8
Evaluation of Viewing Displays	"We compared the cybersickness produced when a virtual environment (VE) was viewed binocularly and monocularly ..." [99]	6

investigation of eye dominance was motivated by binocular rivalry, where one eye's view predominates over the other. These articles demonstrate mixed results. Some indicate eye dominance as a significant factor in binocular rivalry, while others do not. Six studies discussed the effect of eye dominance on depth perception [158, 62, 136, 148, 7, 124]. They aimed to confirm whether eye dominance changes depth perception. For instance, Khan et al. [62] study the assumption "that the perceived location of the virtual object is biased in the direction of the dominant eye".

Three studies explored if and how eye dominance affects pointing and gesturing [92, 64, 2]. Here, the focus does not lie in novel interaction techniques. Rather, the articles aimed to understand eye-hand coordination during pointing in mid-air and on touch surfaces. Two articles offer fundamental research on vision and eye

movement, investigating dynamic visual acuity [31] and line-of-sight displacement during stationary viewing of objects [45].

2.4.3.2 3D User Interfaces

Another motivational aspect of implementing eye dominance HCI is evaluating and developing accurate and efficient 3D Input techniques. A total of 15 studies were motivated by this theme.

Within this overarching theme, six articles evaluated cursors, varying presentation and technique [72, 137, 141, 140, 153, 142]. Studies within this theme highlight parallax, also described as depth- or stereo cue conflicts, as a central problem in 3D interaction and selection. Among others, the application domain covers pointing in a VR fishtank [141, 142, 153], binocular cursors [72], and monocular cursors [140].

Next to the specific work investigating cursors, six studies explored distance selection or pointing techniques [35, 119, 120, 82, 104, 90]. They fall within the areas of novel techniques for pointing and selection in VR [35, 90, 104, 119, 120] and vision-based correction methods [82]. The general motivation of these papers is that pointing is slightly better with the dominant eye than with the non-dominant eye, and that it is easier (or more precise) to specify the object a user is looking at.

Three studies primarily focused on developing touch input techniques for 3D environments (and not on mid-air pointing or selection) [144, 73, 57]. Here, eye dominance is used during parallax correction [57], mid-air touch [73], and touching objects displayed on stereoscopic 3d displays [144]. These papers include eye dominance to better understand the user's perspective and, thus, enhance interaction.

Overall results are mixed, yet indicate using monoscopic cursors in the dominant eye is promising, as it can remove depth conflicts in 3D. Using the dominant eye's view has enhanced pointing accuracy, reduced double vision artifacts, and outperformed a baseline technique. These approaches can enhance interaction with 3D user interfaces, such as optimizing for transparent displays, image-plane pointing or 3D selection while ensuring user comfort.

2.4.3.3 (Energy) Optimization

A sum of eight articles explored various techniques that leverage eye dominance to optimize the energy consumption of display technology [155, 124, 53, 86, 130, 128, 93, 54]. This includes optimization of coding schemes [53, 54, 128], rendering [130, 86], streaming of 360° video [93], as well as improving content delivery for 3D content [124] and power saving [155]. Generally, the notion is that content shown to the dominant eye is much more important than that shown to the non-dominant eye, and this can increase the efficiency of encoding, delivery, and rendering, while remaining imperceptible to the user.

Findings across studies are varied, but overall, leveraging eye dominance had positive effects on energy optimization. Studies found that using eye dominance to guide rendering strategies, such as applying vignette blur or foveated rendering to the non-dominant eye, can effectively reduce display power consumption or increase rendering speed with minimal impact on task performance. However, one study reported increased visual discomfort when resolution differences between the eyes were large, and two studies reported conflicting findings on whether eye dominance influences perceived quality in asymmetric video streaming.

2.4.3.4 Evaluation of Viewing Displays

Five studies assessed the quality of displays or the viewing experience, considering eye dominance during their evaluation. They particularly focus on monocular head-mounted displays (HMDs) and compare them to regular HMDs under various viewing conditions [143, 99, 30, 55, 69]. These studies evaluated viewing experience and performance [143, 30], the explicit influence of eye dominance in HMDs [55, 69], and the effect of ocular dominance on cybersickness during monocular viewing [99].

2.4.4 Utility and Impact of Eye Dominance in HCI

This section outlines how eye dominance has been used in HCI and its observed impact. Core themes here are content presentation (25 in binocular displays and 6 in monocular displays), calibration or online calculations (5), post hoc analyzes only (8), discussion only (5), or testing only (2). Table 2.11 provides an overview of the different categories of how dominance was used in HCI.

2.4.4.1 Binocular Interaction & Content Presentation

Of the reviewed studies, 26 articles present content only in the dominant eye in binocular conditions. Fifteen investigated asymmetric content presentation, while nine investigated user interfaces based on cursors and content placement.

2.4.4.1.1 Asymmetric Quality Presentation Fifteen articles leveraged the dominant eye by presenting content quality asymmetrically and varied between the dominant and non-dominant eyes. This asymmetric presentation encompassed quality [150], foveation levels [86], contrast [151] or blur [135] between both images. These papers aimed to explore an assumed perceptual effect to conserve resources or enhance performance.

Eye dominance can generally be leveraged to reduce energy consumption by lowering the quality of images presented to the non-dominant eye. When applying a higher blur towards the non-dominant eye, no perceptual difference was noted [156, 135, 32]. However, when rendering content asymmetrically with different resolutions, subjects felt more discomfort when the difference between both eyes was too large [130]. No differences between the eyes were found when higher contrast images were presented

Table 2.11: Themes of eye dominance operationalization in HCI work

Eye Dominance Operationalization	Description	N
Binocular Interaction & Content Presentation	Asymmetric Quality Presentation: Some form of content was presented with different qualities or visualizations for the dominant and the non-dominant eye.	15
	Asymmetric Content & Cursors: Content/cursors are presented only to one eye in binocular setups. "In one-eyed mode, the cursor was displayed only to the viewer's dominant eye" [140]	10
Monocular Interaction & Content Presentation	Content was presented in monocular conditions. Device itself was monocular.	6
Offline Calibration & Online Calculation	"In aperture selection, the apex of the conic selection volume, the 'from point', is set to the location of the participant's dominant eye and the direction vector of the cone is the vector from that eye through the tracker's location (represented in the VE by a cursor)." [35]	5
Only Post Hoc Analysis	Studies analyzed the effect of eye dominance, which was not a factor or part of the experiment.	8
Only Discussion	Eye dominance was discussed theoretically as a potential influence on results. [47]	5
Only Testing Reported	Only eye dominance testing reported. No implementation or analysis involving eye dominance.	2

to the dominant eye [151]. Applying a lower-quality video to either eye does not make a substantial difference in the subjective quality assessment [93].

Regarding coding and compression, the results are mixed but promising. There were no significant differences between quality ratings when coding content asymmetrically [128] The influence of eye dominance becomes more pronounced as the asymmetry in coded view quality increases—for example, right-eye dominant users perceive a higher overall quality, regardless of the actual quality of the right eye [53]. Kalva et al. [54] report similar results, indicating that the asymmetric coding needs to be tailored to the dominant eye as it otherwise impairs 3D perception.

Integrating eye dominance into foveated rendering leads to acceptable perceptual quality when a higher foveation level is presented to the non-dominant eye [86]. While the global quality reduction as in foveated rendering is promising, implement-

ing a vignette in VR (and by that, reducing the field-of-view) induced a high level of sickness in participants [155]. Eye dominance does not affect the perception when distorting content asymmetrically in experiments by Wang et al. [150]. However, the distortion of single-view images of a 3D video was perceived, but only when presented to the dominant eye in an experiment [7].

Other aspects investigated in the binocular content presentation are global brightness and saturation. Brightness is biased towards the dominant eye (brighter), whereas saturation seems to be biased towards the non-dominant eye (more saturated) [161]. In addition, when presenting content with less visual interference (crosstalk) to the dominant eye, less visual interference overall is perceived, but only up to a limited amount. Too much makes it noticeable and does not work with a white background [63].

In summary, leveraging eye dominance in asymmetric view presentation generally leads to promising results that are undetectable by viewers. However, it is important to ensure that the disparity between the dominant and non-dominant eye remains moderate, as this can otherwise lead to user detection and symptoms of cybersickness.

2.4.4.1.2 Asymmetric Content & Cursors Eleven studies presented only content or cursors to the dominant eye in binocular conditions [47, 30, 141, 140, 101, 137, 32, 120, 72, 142, 158]. These differences in binocular content presentation yielded mixed results regarding perception and visual comfort.

Hill et al. [47] found that placing a virtual cursor in the dominant eye field worked effectively for image plane selection. In contrast, Ellis et al. [30] observed that using a visual cursor to trace a moving target in binocular conditions caused more eye and neck strain than monocular viewing. Teather et al. [141] demonstrated that displaying the cursor in the dominant eye reduced diplopia (double vision) and improved performance for depth targets, but this approach also led to increased movement time in a Fitts´ law pointing task [140]. While displaying the main content to the dominant eye and other content to the non-dominant eye is practical under specific conditions [101], participants have expressed a preference for stereo cursors, which reduce eye fatigue without significantly affecting completion time [137]. Other findings suggest that rendering annotations from the perspective of the dominant eye improved subjective label quality compared to regular label layouts [32]. Differences in selection time were insignificant between using a one-eyed mode and a dominant eye mode when displaying a binocular cursor [72]. Modulating gaze input by alternating between the dominant and non-dominant eye does not show significant differences [120]. Finally, not investigating an interaction technique or a display, Sgroi et al. investigated iris recognition systems. Their results suggest that eye dominance partially influences the accuracy of iris biometric recognition systems [129]. Using the left eye of left-eyed individuals demonstrated an improved performance of iris recognition. However, this effect was not seen in right-eyed

subjects. Nevertheless, the authors suggest when implementing a two-eyed iris recognition system, the two irises should be weighted unequally for left-eyed users.

Generally, it is not yet well understood in which contexts a monocular cursor within a binocular display is preferable and when content should be shown only to one eye or the other (or alternating). Furthermore, how shifts in eye dominance impacts these methods has not yet been explored. Nevertheless, these initial results are promising in regards to selection accuracy and user experience.

2.4.4.2 Monocular Interaction & Content Presentation

Six other articles leveraged the dominant eye in monocular viewing conditions or interactions. In contrast to the previous category, in this work, a monocular display was worn ([55, 69, 143]) or one eye was patched ([148, 99, 62]).

Research comparing the effects of monocular displays on the dominant and non-dominant eyes reveals minimal performance differences across various tasks. Kancler et al. [55] found that participants performed equally well during static maintenance tasks regardless of which eye was covered. Similarly, LaFleur et al. [69] and Valimont et al. [143] observed no significant performance differences during target search and detection tasks, respectively, whether the display was worn over the dominant or non-dominant eye. However, removing stereopsis by covering the non-dominant eye negatively impacted learning performance in physical anatomy models compared to binocular vision [148]. Patching the non-dominant eye in VR reduced cybersickness [99]. Depth perception was accurate in both monocular and binocular conditions, and subjects tended to perceive objects farther than their actual location [62]. However, there was no shift in perception toward the dominant eye when viewing a 3D object with a see-through AR device [62]. This implies that leveraging eye dominance for monocular content presentation is a less promising approach to exploit for increased performance or user experience.

2.4.4.3 Offline Calibration & Online Calculation

Five articles used eye dominance for calibration [73, 35, 157, 90, 5]. The general assumption has been that accounting for eye dominance enhances the effectiveness of interaction techniques.

Using the dominant eye position to improve touch interaction in 3D environments demonstrated improved performance (task completion time and operation count) compared to a baseline widget-based ray casting method [73]. When calibrating an aperture-based selection technique for VR relative to the dominant eye, participants reported positive experiences with the approach [35]. In an EOG-based communication system, placing electrodes around the dominant eye resulted in high accuracy and processing speed [157]. More reliable parameter estimates were obtained by integrating information about the users' dominant eye into an optical see-through head-mounted display (HMD) model, leading to improved calibration,

alignment, and visual stability [5]. Additionally, when pointing at objects in real space, considering the dominant eye's field of view was highly effective [90].

Overall, leveraging the dominant eye in various interaction techniques and systems has demonstrated high performance, accuracy, and user satisfaction across different applications in 3D environments, VR, and communication systems (although in a few studies). However, these results require verification in further work comparing eye dominance-based approaches with standard techniques. Nevertheless, integrating information about the dominant/non-dominant eye during calibration or in real-time is a promising research avenue.

2.4.4.4 Others: post hoc, testing, discussion

15 studies did not explicitly operationalize eye dominance within their work (i.e., did not use it during implementation, calibration, or study). Instead, they use eye dominance during post hoc analysis (8), report only that they tested for eye dominance (2), or talk about eye dominance in the discussion (5).

Eight investigated eye dominance effects in a post hoc analysis based on general eye dominance tests of their subjects [144, 158, 136, 92, 64, 31, 45, 2]. Four works investigated eye dominance not as a factor but only as a posteriori for touching and pointing. Valkov et al. [144] found that users tend to touch a 3D rendered object on a 2D surface between the projections for the two eyes, with an offset towards the projection for the dominant eye. Related, the post hoc analysis of Akkil et al. showed that more errors are made in the left direction for left-eye-dominant participants, suggesting that hand-pointing interpretation is influenced by eye dominance [2]. A post hoc analysis showed that touch positions in 3D are influenced by eye dominance, resulting in touch positions concentrated near the dominant eye's image [64]. When split by the dominant eye during post hoc analysis, participants with left-eyed dominance also tend to complete pointing operations faster than those with right-eyed dominance [92]. Not investigating pointing but perception, Yang-Mao et al. checked for the effects of eye dominance on depth perception in VR but did not find a significant difference [158]. When averaged across participants, dynamic visual acuity is not different between the dominant and non-dominant eye, and the ocular dominance effect depends on the visual target shape [31]. Finally, measuring the visual axis from a fixation distance showed that the line of sight of the non-dominant eye was nearer to a fixation target than that of the dominant eye [45]. Eye dominance also demonstrates visual priority in decision making when determining the direction of moving objects [136]. When participants viewed two overlapping virtual balls moving toward them and then splitting horizontally (left and right), they chose the ball moving in the direction of their dominant eye. No such effect was observed with vertically moving targets.

These studies contribute to findings from controlled experiments that eye dominance affects touch accuracy and pointing speed (cf. 2.4.4.1.2) and suggest effects on

decision-making in specific contexts, such as tracking moving objects. While it further shows the influence of eye dominance in HCI and how it shapes performance and user experience in nuanced ways, particularly in spatial interpretation and precision tasks, these influences have been detected only through post hoc evaluations and require further verification in controlled factorial experiments.

Five studies do not test or implement eye dominance but consider it in discussion as a potential factor influencing the outcome [57, 119, 153, 104, 124]. Qin mentions that eye dominance probably does not significantly affect selection techniques in 3D environments based on phone occlusion techniques [119]. Ware et al. [153] suggest that eye dominance should be considered when presenting monocular cursors, as it may help reduce user discomfort. Pierce [104] states that, for stereo systems, rendering the selecting hand differently for each eye or only to the dominant eye's image might improve performance. Later articles have picked up this suggestion (cf. Section 2.4.4.1). Studies on factors like image contrast, content, eye dominance, and dark adaptation could be beneficial when designing 3D experiences for users with glasses [124]. Additionally, knowledge of a user's dominant eye could improve the accuracy of touch interaction [57]. Finally, two studies only reported testing for eye dominance but do not integrate it in implementation or analysis [82, 70].

The fact that many studies only consider eye dominance in later stages of the research process suggests a missed opportunity. Research on content presentation, 3D environments, calibration, depth perception, and rendering would benefit from integrating eye dominance early on—either as a design factor or as a recorded demographic variable to allow for meaningful post hoc analysis. This would foster research and, as our synthesis suggests, increase the effectiveness of techniques.

2.4.5 Summary and Key Findings on Eye Dominance in HCI

In summary, HCI conceptualizes eye dominance in a simplified manner and frequently as a fixed trait while neglecting the range of physiological, perceptual, contextual, and individual influences identified in vision science (cf. Section 2.3.3). The fact that eye dominance is considered across multiple fields in HCI, particularly in visual 3D interactions, underscores its relevance and potential. It has shown promise in enhancing performance, accuracy, and user experience in various 3D applications (such as AR and VR), including rendering, interaction techniques, and content presentation. However, only a few studies report on their testing method, and even fewer provide a detailed description of their procedures and parameters used. A more thorough and transparent approach to documenting testing would benefit the interpretation and replicability of the studies. Incorporating eye dominance as an early factor in HCI research, whether as a design consideration or a demographic variable, could support more nuanced analyses and lead to the development of more adaptive and effective user-centered technologies.

2.5 Discussion

This systematic literature review aimed to provide an understanding of eye dominance (focusing on sighting eye dominance). It describes the current understanding of eye dominance in HCI and provides insights for the HCI community from vision science. To do this, we analyzed relevant vision science literature regarding eye dominance definitions, testing methods, influencing factors, effects, and relation to other dominance types. In addition, we queried HCI work that integrates or discusses eye dominance about the applied definitions, motivations for using or discussing it, how eye dominance was tested and implemented, and what effects eye dominance had on experimental outcomes.

Our review shows that, especially in vision science, research on eye dominance has a long history. Still, for sighting dominance — the focus of our review — the definitions of eye dominance are not in agreement. While about half of the reviewed papers define it as a preference, others use definitions relying on functional differences (e.g., that the dominant eye leads), task, laterality, or the testing method (Section 2.3.1). HCI research, most likely inspired by vision science literature, is similarly split in how eye dominance is understood and defined in the papers (cf. Section 2.4.1).

These differences in understanding and defining eye dominance, e.g., preference vs functional differences, are reflected in the factors that have been shown to influence eye dominance in vision science literature. For example, while preference points towards an individual predisposition (similar to hand preference), others, such as task and testing method, point towards more contextual factors (such as viewing angle) — as outlined in Section 2.3.3. It is important to note that evidence is only strong for some factors (e.g., hand preference, horizontal viewing angle). For others, while some studies suggest a factor to be influencing, research does not agree, necessitating further investigation (e.g., hand used during motor movement or viewing distance). Vision science has, however, provided strong evidence for perceptual superiority of the dominant eye in a variety of studies (cf. Section 2.3.4).

Research in both HCI and vision science is similarly fragmented when it comes to testing methods (cf. Section 2.3.2 and Section 2.4.2). While there are many, there is no standard procedure for testing eye dominance, preventing a direct comparison of reported results on eye dominance (cf. Section 2.3.2). This is problematic as the most common methods produce different outcomes. In addition, both vision science and HCI rely heavily on static testing of eye dominance with tests like the hole-in-card or Miles test, neglecting the influence of factors such as viewing angle.

So far, HCI mainly relies on the understanding that eye dominance is influenced only by individual factors, specifically, that it is static and the applied test provides a universally dominant eye. Thus, as of now, HCI does not fully reflect on and integrate contextual factors. Still, the wide range of successful applications of eye dominance in HCI — human factors, 3D user interfaces, optimization, and evaluation — underscores its relevance and the increasing interest in harnessing it

(cf. Section 2.4.4). This suggests that eye dominance is a promising property for HCI — albeit one that demands careful consideration and precise, in-depth investigation and integration.

Together, our review highlights that sighting eye dominance is a nuanced concept. Despite the long research history on the topic, eye dominance is not yet fully understood. Both vision science and HCI would therefore benefit from a new or updated definition of sighting eye dominance. This definition should reflect both the functional effect of eye dominance (e.g., physiological and perceptual differences between the dominant and non-dominant eye) as well as its dependency on individual and contextual factors (e.g., handedness and horizontal viewing angle). It also shows that testing methods need to be rigorously applied and reported, but also that they need to evolve so that they capture these nuances, especially regarding factors influencing eye dominance.

2.5.1 Leveraging Vision Science for HCI Practice

With this work, we set out to provide insights on eye dominance for the HCI community. Based on the systematic literature review, two core themes emerged on how HCI researchers can leverage findings from vision science to better integrate eye dominance into their research: improved definition and testing procedures and considerations for design and development by distinguishing between momentary and baseline eye dominance.

2.5.1.1 Definition, Reporting, and Testing

A practical implication of this review is the recognition of multiple types of eye dominance (e.g., sighting, sensory, motor) and reporting on which type of eye dominance a particular HCI work is based on (cf. Section 2.3.1). In addition, we encourage HCI researchers to move beyond simply framing eye dominance as a mere 'preference' and engage with other, more context-aware definitions. Next to mentioning the type of eye dominance, we recommend researchers report in the manuscript (e.g., in the design section for an interaction technique) their theoretical understanding of how eye dominance behaves: influencing factors and what effects it has. Ultimately, this should lead to a shared understanding of eye dominance.

To address the lack of standard testing procedures, we recommend the hole-in-card test (cf. Section 2.3.2.1) for general testing in real-world contexts, as it is the most widely used (36 out of 114 vision science articles) and regarded as the most reliable method in vision science [44]. Researchers must report the parameters they used (e.g., card size, hole size, target distance). We advocate for developing real-time prediction techniques to support more accurate and robust classification of eye dominance in dynamic and interactive environments. This will be addressed in Chapter 7, where we explore the use of context- and user-specific features for eye dominance prediction.

2.5.1.2 Design Considerations: Momentary vs. Baseline Eye Dominance

As an HCI designer considering eye dominance, it is necessary to understand that some influences of eye dominance are under the designer's control, while others are not. Influences may originate from the user's inherent traits, such as hand preference or pre-existing eye conditions, which opens opportunities for personalized design (cf. Table 2.7). Designers can query these details to personalize the dominant eye per user. Still, as the results do not show a perfect correlation, it is recommended that users have the option to override the settings. On the other hand, other influences of eye dominance are contextual and stem from the task or current activity (cf. Section 2.3.3.2). Here, factors such as the hand used during motor tasks, horizontal viewing angle, and potentially viewing distance might influence which eye dominates at a given moment. These factors usually vary between and during tasks, leading to dynamic changes in eye dominance during the interaction. Designers can anticipate, integrate, and react to these changes, updating the current dominant eye to establish a context-aware integration of eye dominance. Integration of the dynamics of eye dominance could be done via rule-based systems (e.g., automatic switching based on viewing angle) or by developing systems that estimate the current dominant eye based on multimodal input (e.g., user profile, viewing angle, viewing distance). This highlights how designers might integrate both individual and contextual factors influencing eye dominance, maximizing potential performance gains from eye-dominance-aware design.

Given the dynamic nature of eye dominance based on individual and contextual factors, it might be valuable to differentiate between momentary eye dominance, where one eye leads during a specific activity (strongly influenced by contextual factors), and baseline eye dominance observed during neutral or central viewing conditions, which strongly depends on individual factors. The relevance of this distinction largely depends on the application and activity. In tasks with minimal gaze shifts, such as reading, a stable and central viewing position is more common, and the likelihood of eye dominance changing is reduced. The distinction between a baseline and a momentary (context-aware) eye dominance has practical implications for the design of gaze-based interfaces, AR/VR systems, and adaptive user modeling. For example, systems may benefit from incorporating real-time dominance detection in dynamic environments, while relying on baseline measures may suffice in more static contexts. Future research should investigate how momentary and baseline dominance behave and differ across tasks.

2.6 Chapter Summary

In this systematic review of 166 articles from both vision science and HCI, we answer the questions of what eye dominance is, how eye dominance is reflected in HCI, and what HCI can learn. Our key findings show that integrating eye dominance early in research on content presentation, interaction techniques, and

visual systems promises to enhance performance and user experience significantly. Our review further highlights the complexity of eye dominance and its relevance to HCI. Particularly, the casual reporting throughout the reviewed HCI work contrasts with the complex understanding in vision research. In HCI practice, acknowledging eye dominance means being mindful of how users might perceive and interact differently based on their dominant eye. In addition, HCI researchers and practitioners should remain aware that eye dominance is not just a theoretical concept but a practical consideration that can affect both research outcomes and the effectiveness of interactive systems. Ultimately, integrating eye dominance within eye-based HCI work promises to enhance applications and techniques, provide deeper insights into user behavior, and allow for better customization and adaptation methods for user interfaces, rendering, and content presentation.

Chapter 3

Dynamics of Eye Dominance Behavior in Virtual Reality

As a first step to investigate eye dominance in practice, we replicated and extended a study from psychology to further examine the behavior. This chapter addresses **RQ 2**. Specifically, we examined factors that influence eye dominance and translated an existing eye dominance testing method into virtual settings, allowing for objective measurement, thus also addressing the sub-questions **RQ 2a** and **RQ 2b**. Khan and Crawford have shown that sighting dominance is dynamic and context-dependent [58]. Specifically, the horizontal gaze angle at which objects are aligned has been shown to influence which eye is dominant. As discussed in Chapter 2, vision science provides strong evidence for hand preference and horizontal viewing angle as influencing factors for eye dominance [58, 61]. Yet, viewing distance as an influencing factor requires verification. Given, that VR contexts largely involve the dimension of depth, we aimed to explore this additional variable.

3.1 Eye Dominance Dynamics

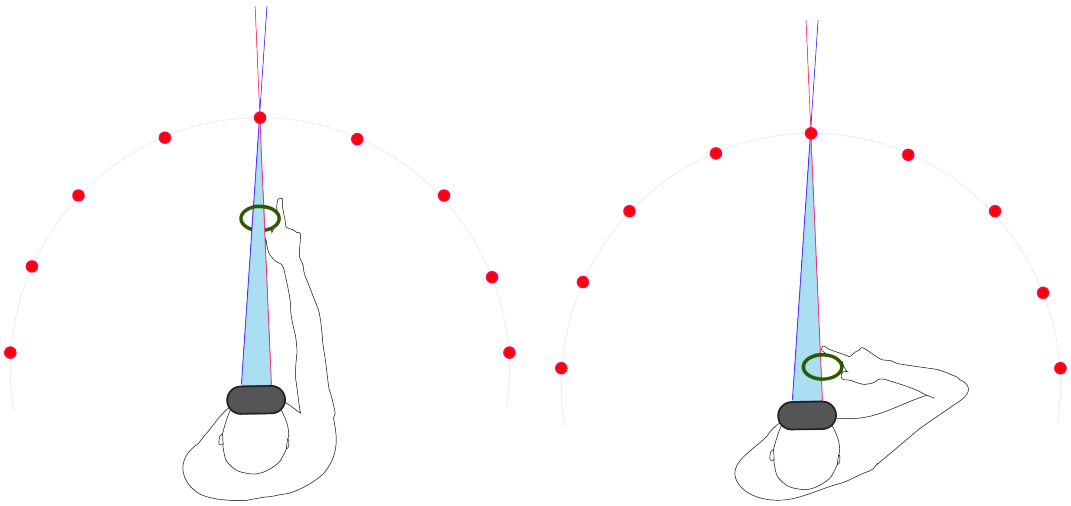
Khan and Crawford demonstrated that crossovers in eye dominance occur when objects are aligned in the contralateral field [58]. Banks et al. suggested this to be explained by the relatively larger image size in the eye that is closer to the object at a given viewing angle [8]. Khan and Crawford adopted an objective approach to determine the dominant eye [58]. Their method required participants to reach and grasp a ring placed around a target and to move the ring towards their face while continuing to fixate the target through the ring. This method ensured that the ring would be brought up close to the one eye dominating alignment of the target through the ring, enabling the investigator to observe and record eye dominance accordingly. The experiment was conducted in a physical environment with targets located at a distance of 0.53 cm to facilitate reach, and placed at different gaze angles. These were presented in a semi-circular array, from central viewing at 0°

to eccentric viewing at 50° to the left or right, in steps of 10°. For central viewing, eye dominance was influenced by individual differences, but at eccentric angles, it depended consistently on the position in the visual field. Additionally, a hand effect was observed with more left eye dominant cases when the left hand was used to grasp the ring and vice versa, relating to other work on the link between handedness and eyedness [15].

3.2 VR for Studying Eye Dominance

VR has become a valuable tool for studying eye movement and human behavior, as it provides flexibility and control in presentation of stimuli in a 3D virtual environment [85]. Variables in VR experiments can be highly controlled, yet the experimental setup may still greatly resemble real-world scenarios that can be replicated with little effort [18]. Within a VR scene, the position of objects presented is controlled and available for analyses, while tracking of gaze, head and hand movement affords precise measurements in relation to targets viewed and manipulated. Eye movement is being studied in VR to support interaction [103]. Previous work has used VR to study the coordination of eye, head and torso movements in gaze shifts [133]. However, eye dominance has not been given any significant attention. Elbaum et al. considered eye-tracking from the dominant versus the cyclopean eye but assumed a static dominant eye [29]. Meng et al. proposed to optimize foveated rendering by giving priority to the dominant eye, optimizing computing resources without compromising perceived visual quality [86]. This approach assumes consistent eye dominance, but by acknowledging the dynamic nature of eye dominance, there is an opportunity to further refine rendering, ensuring optimal visual quality under varying conditions. Wagner et al. studied gaze-assisted selection in a VR environment by perspective pointing with a finger in the line of sight and found performance to deteriorate when targets were at a greater distance from the finger, indicating the relevance of eye dominance for interactive tasks in VR [147]. Adapting perspective pointing techniques to account for the dynamic changes in individual eye dominance behavior would have the potential to greatly enhance the precision of distance pointing in 3D environments.

In this chapter, we propose the use of VR for research on eye dominance. We adapt Khan and Crawford's method for use in a virtual environment and show how this facilitates automated classification of the dominant eye. We replicate the original study on the dependence of eye dominance on gaze angle and hand used to demonstrate that behavior in VR corresponds with behavior in a physical setup. In the original study, only targets that were in reach were used. We take advantage of VR to include targets that are rendered at a greater distance but scaled in size. To the participant, distant targets appear the same size as targets placed in reach, and their alignment action is the same irrespective of target distance (i.e. they do not need to reach any further to find the ring fully surrounding the target). The distance conditions will appear identical in the 2D projection plane but involve increasing



(a) Start of Movement (b) End of Trial

Figure 3.1: Task Movement. a) The participant focuses on the target and starts by placing the virtual ring around the target. b) The participant moves the ring closer to their head while continuously fixating on the target through the ring.

disparity in focal depth between ring and target. Our motivation for testing larger distances is to ideally show that the focal disparity does not affect eye dominance, as that would provide greater flexibility for the design of methods that infer eye dominance from interaction in VR.

3.3 Method

We propose using VR to study eye dominance in stereoscopic head-mounted displays (HMD). Modern stereoscopic VR HMDs consist of two displays each providing visual input to only one eye, which creates the experience of a 3D environment. When using VR, users can hold a physical controller that is represented by a visual marker, cursor or object within the VR experience, while the hand itself and any other physical "real-life" surroundings are not. In turn, the HMD prevents surrounding observers from seeing the user's eyes. If the HMD is equipped with an eye tracker, information about the eyes is available. The eye tracker used in this work (Tobii Pro Research v1.1) provides both monocular information of each eye (position and direction) and cyclopean gaze (origin and direction). For our analysis, we rely on the reported monocular information of each eye. The field-of-view (FOV) provided is wider than on conventional displays but narrower than our real vision. The HTC Vive, used in this work, has a 100° horizontal and 110° vertical FOV.

In VR, we can determine eye dominance based on tracking of a manually controlled cursor that participants first need to align with a target in the virtual environment, and then move backwards while keeping it aligned with the target, as illustrated

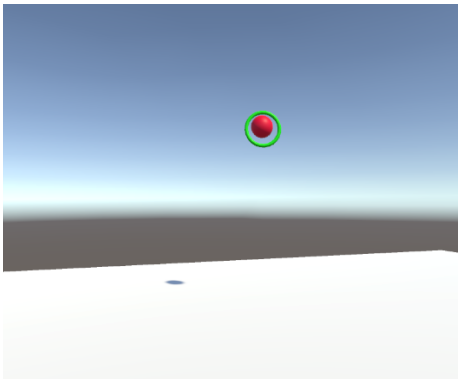


Figure 3.2: VR Task Screenshot. *Note.* Participant views the distant target and aligns the virtual ring around it. The green color confirms the correct placement and signifies the participant to initiate the movement towards the head.

in Figure 3.1. The target locations are fixed to the virtual camera to follow the user's head movements. This provides control over the gaze angle without need to constrain head movement. VR affords flexibility in the placement of targets. To replicate Khan and Crawford's work within the limits of the available HMD, we placed targets in range from a -40° to 40°, at 10° increments. In the original study, targets were 3cm in diameter at a 0.53m distance. We implement targets in VR at the respective angular size of 3.2423° which corresponds to a perceived target size of 3cm, regardless the distance. However, we vary the depth at which targets are rendered in the virtual environment to appear at distances of 0.53cm, 1m, and 3m from the viewer. Note, that targets appear at the same perceived distance to the participant, irrespective of their distance.

VR allows flexibility in how cursor and targets are rendered and placed in the environment. However, to replicate Khan and Crawford's original study, we adopt a ring as the cursor and targets that fit within the ring when they are aligned, as shown in Figure 3.2. The position of the ring is controlled with a handheld controller, as shown in Figure 3.3, and continually tracked. An alignment trial starts with a target appearing in the virtual environment. The participant is tasked to align the target by placing the ring around the target. Visual feedback is given by changing the ring color when the participant reaches a preset depth in the virtual environment, set to 53cm to reflect the original setup. The reaching distance is the same in all target conditions, but larger distances induce a focal disparity between the ring and target. To avoid a collision of the controller with the HMD in the backward movement, we also placed a virtual collider just in front of the HMD. Once the virtual ring reaches this collider, a notification sound signals that the trial has been completed. In the work by Khan and Crawford [58], the respective eye over which participants placed the ring at the end of the movement was manually labeled as dominant by visual inspection of the video-recorded user. In VR, we can automate the classification. We track the backward movement of the ring and at the end position and measure

(a) Start of Trial

(b) Completion of Movement

Figure 3.3: Participant during VR task sequence.

the distances from either eye (Figure 3.4). The eye that is closer to the ring is labeled as the dominant eye. To do this we used eye tracking data provided by the HMD. The eye tracking data was exclusively utilized for trial validation. This approach allowed for an automatic dominant eye classification procedure. Note, since participants are wearing an HMD, they cannot fully reach their eye as the original study did (Figure 3.3b). The HMD adds 10cm in depth, and in post-hoc analysis, we found that the final distance of the ring from the dominant eye was on average at M=12.74cm (SD=0.92cm). This close to the face, the difference in distance to either eye is pronounced, providing a robust measure for classification.

3.3.1 Study

The objective of this study was to replicate Khan and Crawford's study in VR. In addition, our aim was to test conditions where targets appear at a greater distance from the viewer, to assess whether the focal disparity present at the start of the alignment affects the choice of dominant eye.

3.3.1.1 Participants and Apparatus

20 participants were recruited (11 male, 8 female, 1 preferred not to indicate gender, M = 31.2 SD = 6.68 years) from our local university. Eight participants reported normal vision, eleven corrected to normal vision with glasses, and one corrected to normal vision with lenses. Participants with corrected vision were asked to wear contact lenses instead of glasses for the study. 14 of the participants reported being right- and six left-handed. Six participants were cross-dominant (e.g., left-hand and right-eye dominant, and vice versa). The standard alignment test showed eight participants were dominant in the left eye, while twelve proved dominancy in the

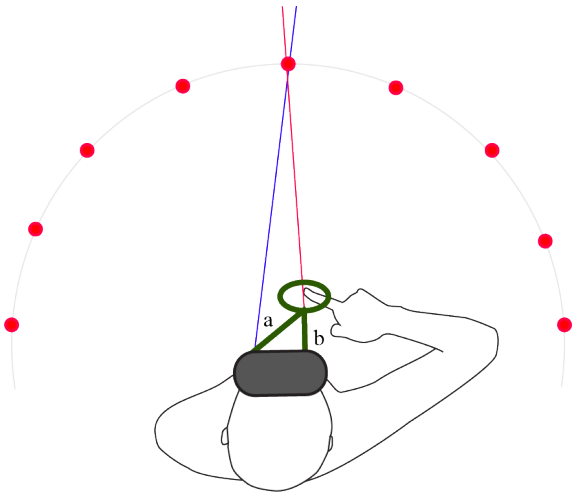


Figure 3.4: Dominant eye classification. At the end of the movement, the distances of each eye to the ring are compared (a and b). The shorter of the two distances (in this case b) classifies the dominant sighting eye.

right [109]. The study setting and its conditions were created with Unity 2020.3.32f1. An HTC Vive (90Hz display refresh rate) with an integrated Tobii Pro Research v1.1 eye tracker (sample rate 120Hz) was used to record hand controller and eye movements.

3.3.1.2 Design and Procedure

The factors studied were viewing angle, target distance and use of left versus right hand:

- Viewing Angle (-40, -30, -20, -10, 0, 10, 20, 30, 40°)
- Target Distance (0.53, 1, 3m)
- Hand used (Left, Right)

As Khan and Crawford reported a hand effect, we also included this as an independent variable. To avoid a bias, the hand used during the trials was counterbalanced with a 3 target distances × 2 hands balanced Latin square. Distinct variable combinations were repeated 5 times, resulting in a total of 270 trials per participant, consisting of 45-trial blocks. Before participation, subjects gave informed consent. Participants completed a short demographic questionnaire and performed a standard alignment test to determine standard sighting dominance. Subsequently, the task procedure was described, which participants could practice before starting the data collection trials. Before data collection, the participant calibrated the eye tracker with a five-point calibration. Additionally, the inter-pupillary distance was adjusted by rotating the IPD knob on the HMD until the visual indicator in the UI turned green, signifying correct adjustment for optimal

depth perception. Participants were instructed to look forward during the study. On average, the study took a total of 45 minutes to complete, with short breaks every 45 trials. The eye tracker was re-calibrated every time participants removed the HMD during breaks. The FST Ethics Committee at Lancaster University ethically approved the study.

3.4 Results

Participants took between 0.85 and 6.34 seconds to complete the movement of each individual trial (M = 2.34, SD = 0.94 seconds). Some subjects reported experiencing double vision of the ring at farther target distances. This was especially the case in viewing angles located toward the center rather than on the periphery. However, some participants denoted that this did not occur at the outermost target angles (40° and -40°) and saw only a single ring and target. One participant mentioned the inability to see targets located at the outermost viewing angles (-40° and 40°). We discarded the data of this participant from the analysis.

3.4.1 Data Cleaning

Before analysis, the data was examined for any tracking inaccuracies. Any data frame labelled as "invalid" by the eye tracker was deemed invalid. A single trial was considered valid only if it consisted of at least 90% valid frames. The data of 6 participants was excluded from the analysis, as the collected data of each participant consisted of less than 90% valid trials. Additionally, the remaining 14 participants, a total of 451 individual trials were discarded from the analysis, as these contained less than 90% valid frames. For the remaining trials, we applied backfill linear interpolation. This resulted in a total of 3329 valid trials from 14 participants available for the analyses.

3.4.2 Binomial Logistic Regression Model

In Khan and Crawford's study [58], the final positioning of the ring in front of subjects' faces was used to indicate the dominant eye. To compare our results to those of Khan and Crawford, we based our analyses on the final data frames of each trial, as these correspond with the final positioning of the ring approximately 10-15cm in front of the subject's face. This assured the closest imitation of the classification in the original study in VR. The following analyses aim to explore whether our VR findings align with those from the real-life study.

A binomial logistic regression was performed to determine the effects of the angle, distance, and hand used on the probability that participants are right-eye dominant. Table 3.1 presents the binomial logistic regression model. The model was statistically significant, $\chi^2(3) = 3009.49$, $p < .0005$. The model explained 79.20 (Nagelkerke, 1991) of the variance in right eye dominance and correctly classified 90.8 of the cases. The

Table 3.1: Binomial Logistic Regression. Target angle and hand used were significant predictors.

Variables in the Equation	**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B)**	**95% C.I. for Exp(B)**	
							Lower	**Upper**
Hand	-1.766	0.141	156.11	1	**<.001**	5.847	4.432	7.713
Horizontal target angle	0.164	0.006	748.246	1	**<.001**	1.178	1.164	1.192
Distance	0.067	0.060	1.268	1	0.260	1.069	0.952	1.202
Constant	-0.859	0.131	43.181	1	<.001	0.424		

Note: Hand is for the right hand, compared to the left.

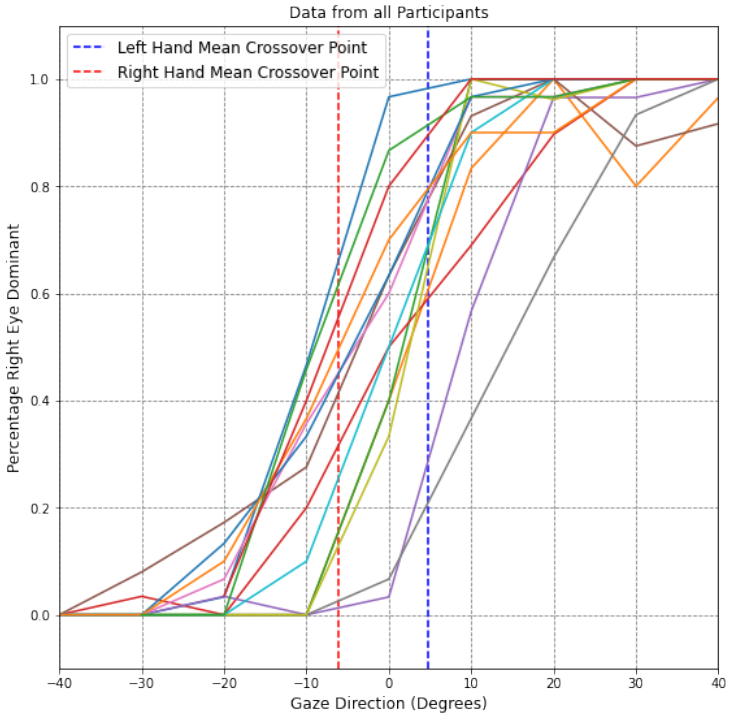


Figure 3.5: Average percentage of right-eye dominance by viewing angle.

sensitivity was 90.40, the specificity was 91.30, the positive predictive value was 91.93, and the negative predictive value was 89.68. Only two of the three predictor variables were statistically significant: viewing angle and hand used to move the virtual ring (as shown in Table 3.1). The probability of being right-eye dominant is 5.847 times higher for trials using the right hand than those using the left hand while holding all other variables constant. Right-handed trials were more likely to be right-eye dominant than right-handed individuals. The probability of being right-eye dominant increases by a factor of 1.178 for every 10° increment in angle, while keeping all other variables constant. Therefore, trials with larger angles (>10°) are more likely to be right-eye dominant than those with smaller angles (< -10°). The area under the ROC curve was .963 (95 CI, .957 to .968).

3.4.3 Target Viewing Angle

Figure 3.5 visualizes the percentage of right-eye dominant cases per viewing angle for each participant, averaged across all trials and target distances. At the outermost viewing angles, all subjects viewed the targets with the eye corresponding to the respective side. Thus, the targets at -40° were viewed with the left eye, while the subjects used their right eye at 40° viewing angles. On average, when using their right hand, participants switched from their left to their right eye at a gaze angle of around -6.13° (SD=9.67), as shown in Figure 3.5 via the line indicating the mean crossover point. For the left hand, the mean crossover point was located at 4.79° (SD=7.80), at which participants switched from their left to right eye.

3.4.4 Target Distance

All three target distances show similar trends in the percentage of right-eye-dominant cases as a function of viewing angle (Figure 3.6). At 0.53m distance and right hand use, participants switched from left to right eye at an average gaze angle of –5.74° (SD=5.27). At 1m targets, when using the right hand, the left to right eye switch occurs at a mean angle of -6.49° (SD=12.44). When viewing targets at 3m and using the right hand, participants switched on average at -9.68° (SD=10.60). However, the average viewing angle at which participants switched from left to right eye did not differ significantly with increasing target distance.

3.4.5 Hand Effect

The influence of the hand's movement on the sighting dominant eye is most pronounced when considering the central viewing angles (-20° to 20°), as depicted in Figure 3.5. The mean crossover points, the angles at which participants switched from their left to their right eye, are shifted, depending on which hand was used to move the virtual ring. Table 3.2 presents the individual mean crossover points and respective standard deviations for each target distance and hand used. 14 of trials are right eye dominant when using the left hand, whereas 79.71 are right eye dominant when using the right hand. At central viewing angles, the right eye is classified more often as dominant, whenever the right hand was used to move the virtual ring. Whenever the left hand moves the ring, the left eye dominates more frequently at the central angles. This shift is independent of target distance.

Table 3.2: Mean crossover angles (average angles at which a dominance switch occurs) and standard deviations for "hand" and "distance".

	0.53 m		1 m		3 m	
	M	SD	M	SD	M	SD
Left	4.93	4.90	3.34	7.11	3.18	10.80
Right	-5.74	5.27	-6.49	12.44	-9.68	10.60

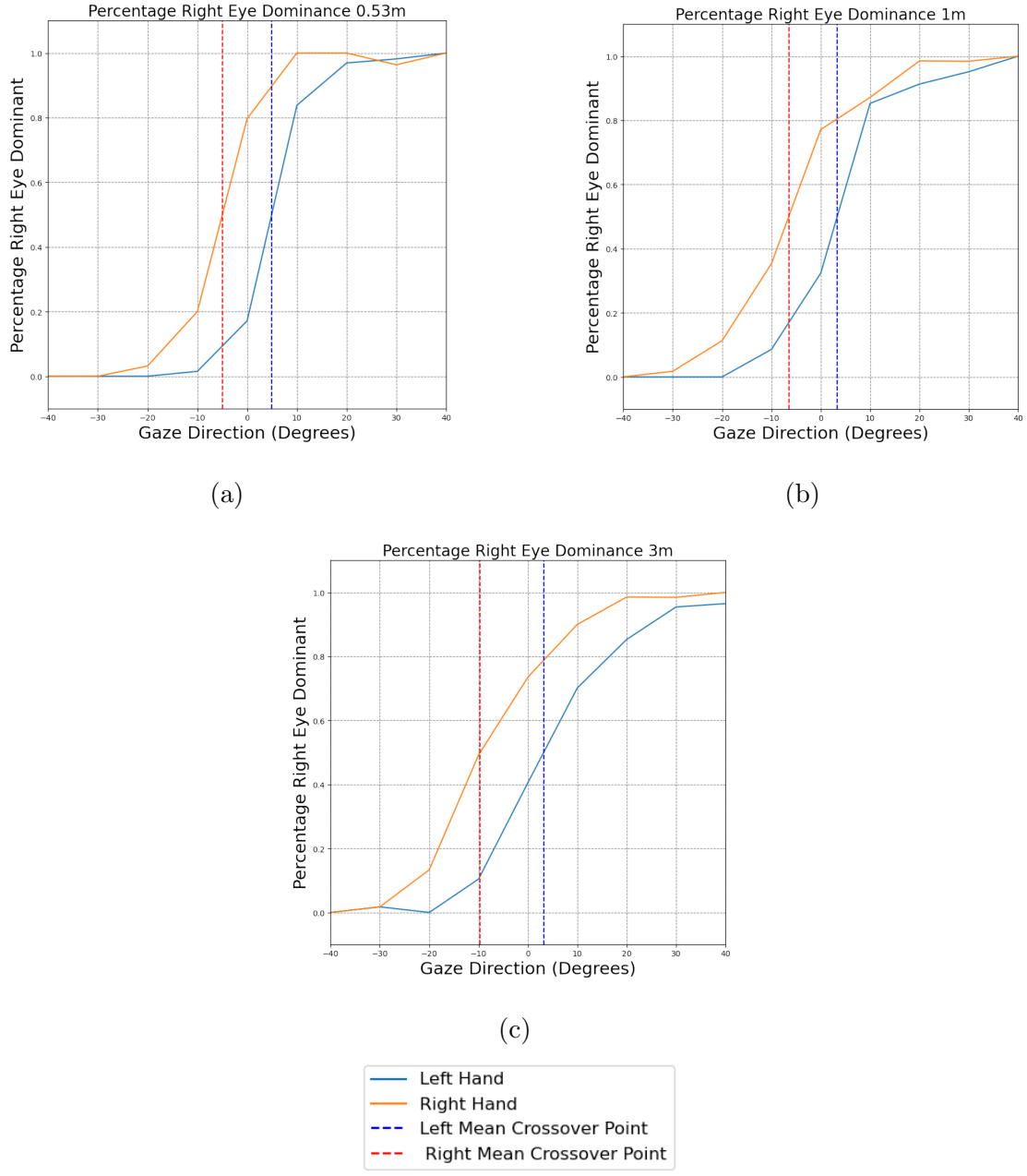


Figure 3.6: Average percentage of right-eye dominance by viewing angle for each target distance.

3.5 Discussion

This study showed that the reversal of eye dominance in response to viewing angle applies within a VR setting, remaining consistent when targets are presented at greater depth. Furthermore, we were able to use eye and controller position to determine the dominant eye automatically in the context of a reach and grasp task.

3.5.1 Eye Dominance Reversal

Our results indicate that the viewing angle and hand used to move a virtual ring to one's face have a significant effect on sighting eye dominance within a VR context. Target distance does not influence sighting eye dominance significantly. Our results generally agree with previous results [58], indicating that their main findings apply within a VR setting, even when targets are presented at greater depths. The use of greater target distances presents opportunities to investigate alignment with objects placed at varying depths, providing greater flexibility for the design of methods that infer eye dominance from interaction in VR. However, it is crucial to implement larger target distances carefully, as extending the target distance will result in double vision. Our results indicate a narrower viewing angle range in which an eye dominance switch occurs than in previous work [58]. Yet, the large standard deviation of mean crossover points and high variability between participants highlight the individuality in the reversal of sighting eye dominance. When considering the mean crossover points for the left and right hand, the effect of the hand contributing to a switch in eye dominance is highly pronounced. We demonstrated that the close positioning of a virtual ring in front of the face will reliably indicate eye dominance.

3.5.2 Limitations and Future Work

Several factors limit the generalizability of this work. Using the HTC Vive headset limits the horizontal FOV of participants to 100°. With that, targets located at -50° and 50° are not visible, leading to the exclusion of these. Furthermore, this study included the use of static targets that are presented in random order only at a constant horizontal amplitude. It is unclear how target sequencing (e.g., from left to right) or differing target amplitudes would affect eye dominance in VR. This work is also limited by its lack of consideration of head and body rotation. The targets were fixed to the virtual camera, meaning they could rotate their head freely, but the target would still appear at the determined viewing angles. A study taking head and torso position and rotation more closely into account could inspect other factors that cause a shift in eye dominance. In addition, further work may develop a "hands-free" approach to classifying the dominant sighting eye. Participants may not be required to use their hands, and the possible influence of hand movement can be discarded. A technique involving two floating targets at different distances may serve as a classification method. In this case, subjects must pivot their head to align

both targets. The influence of eye dominance on stereo acuity remains uncertain. However, there is evidence of a bias in the 3D location of objects, with eye dominance being considered a contributing factor [58]). Future work should investigate the relationship between eye dominance and stereo acuity, simultaneously examining the participants' FOV to understand the impact on the virtual experience.

3.6 Chapter Summary

This work replicates a real-life study setup of eye dominance within a VR context. In conclusion, the factors inducing a reversal of sighting eye dominance also apply within VR, remaining consistent when targets are presented at greater distances. Horizontal target viewing angle and the hand used to move a virtual ring towards the face influence a switch in sighting eye dominance. This work is a first step in examining the behavior of eye dominance within VR and using eye and controller position as a means of classification. The results obtained in a VR set-up align with real-world study results.

Chapter 4

Comparing Eye Dominance Testing Methods

Building on the findings and lessons learned from our initial study presented in Chapter 3, which explored the dynamic eye dominance behavior in VR contexts, we detected eye dominance by observing which eye users used when they moved a virtual ring towards their face. While effective, this procedure proved as unnatural and time consuming. To address this, we opt for a more naturalistic and embedded method for detecting eye dominance, enabling a faster and more intuitive calibration. In this chapter, we compare three traditional eye dominance tests to see how much they agree with their outcome, addressing our sub-research question **2b**. Furthermore, we designed an in-HMD eye dominance test (Virtual Hole-in-Card Test) and contrast its results with the traditional tests.

4.1 Eye Dominance Testing Methods

To exploit eye dominance, researchers need to know which eye is dominant. Thus, participants' dominant eye must be determined before or during studies. Here, psychology and vision science provide several testing methods to determine the dominant sighting eye. Among others, the Miles test, the hole-in-card test, and the point test are prominent. While all of them have the same objective, determining the dominant eye, they differ in how this is achieved. Some tests rely on the participant reporting their dominant eye [3], and some rely on the experimenter observing [88].

Yet, prior research criticizes these tests, suggesting that they do not always agree [160, 24]. Comparing these methods is crucial for improving their consistency and identifying the most reliable approach. A standardized testing method is missing in extended reality (XR) work, leading researchers to adopt various available tests. While this is acceptable for research and laboratory studies, requiring a dedicated step outside the head-mounted display (HMD) potentially degrades the

onboarding experience, making it challenging to test and deploy eye-dominance-based technologies at scale. Here, a method for determining the dominant eye in the HMD within the eye tracking calibration process would streamline this process. The following section briefly describes the three most prominent traditional eye dominance tests and our in-HMD testing method.

4.1.1 Traditional Eye Dominance Testing Methods

Which eye is dominant is reported to depend on the test method used [24, 89]. Many methods measure or determine the dominant eye, yet these can differ significantly in procedure and outcome [160]. The commonly utilized methods are the hole-in-card test (also known as the Dolman test) [1], the pointing test (referred to as the Porta test or near-far-alignment test) [71], and the Miles-test [88]. Given the nature of these testing methods, sighting eye dominance is measured in monocular situations, requiring a conscious or subconscious choice between the two eyes [17].

4.1.1.1 Miles-Test

During the Miles-Test (cf. Figure 2.3c, Chapter 2), participants are instructed to look at the experimenter through a small hole [88]. The hole can be an object (e.g., a cone as illustrated in the picture) or, alleviating the need for external objects, a triangle shaped with their hands. Through the hole created, participants are instructed to focus on the experimenter's nose, who stands a few meters before them. The experimenter then observes which eye the participant aligns with the hole and records that eye as the dominant one. Thus, it is not the participant who indicates what they see, but rather the experimenter who determines which eye the participant tends to use to align with the stimulus.

4.1.1.2 Hole-in-Card

The hole-in-card is also known as Dolman test and is completed using a card with a central hole (cf. Figure 2.3a,Chapter 2 [19]). Participants typically hold the card with both hands reached out in front of them. Through the hole, subjects view a distant target. Participants are then instructed to alternate the closing of one eye and indicate whenever the target is no longer seen through the hole in the card. The open eye, in which the target is still visible through the hole, is dominant. Here, the participant reports the outcome.

4.1.1.3 Point Test

The point test (see Figure 2.3b, Chapter 2), also known as the Porta test, follows a similar method to the hole-in-card test [113]. Instead of holding a card, participants point at a distant target. Then, they alternate closing one eye and indicate whenever the target is no longer pointed at. The eye with which participants still point at the target is determined as dominant. Again, the participant reports the result.

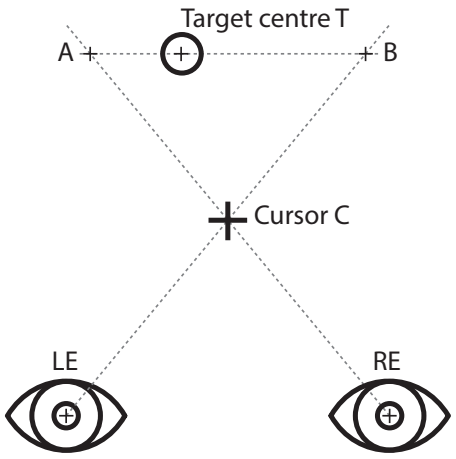


Figure 4.1: Distance-based measurement for eye dominance classification in VR. The distances from each eye-cursor ray ($\overrightarrow{RE\ C}$ and $\overrightarrow{LE\ C}$) to the center of the target at target height are compared ($\overrightarrow{A\ T}$ and $\overrightarrow{B\ T}$). Here, $\overrightarrow{A\ T}$ is smaller, indicating right-eye dominance.

4.2 Automatic Virtual Hole-in-Card Test

Based on the classification method described in the previous chapter (Chapter 3), we developed an automatic geometric classification method for eye dominance in VR. Lessons learned from the previous study informed a new metric which no longer requires participants to align and move a virtual ring towards their face. Instead, participants are required to align a virtual cursor and a target with their line of sight. The dominant eye is determined using the target position, the cursor position, and the position of the eyes. This eye dominance detection during simple alignment allows for a more naturalistic and unobtrusive procedure. Figure 4.1 illustrates determining eye dominance with this approach. The cross (+) represents the VR cursor position (center of a hole-in-card), while the ring (∘) marks the target's center. The dashed lines depict (invisible) rays from each eye passing through the cursor's center. To identify the dominant eye, we measure the distances between the target's center and each line along a line that extends through the target and runs parallel to both eyes, assigning dominance to the eye with the shorter distance. The dominant eye is then determined after an alignment period of 100 frames.

In our implementation, a virtual round target (3.2423°) and a rectangular card (10×10 cm) with a dynamically adjustable central hole (3.2423° in size) were attached to the controller. This setup emulated the traditional hole-in-card technique. Participants viewed the target through the hole while aligning the target, cursor, and one eye. The card enforced precise alignment of one eye with the target, reducing parallax and double vision effects. Khan and Crawford [58] positioned targets 0.53 cm away from participants with a 3 cm diameter. In contrast, we placed targets at a 2 m distance to induce a noticeable parallax effect and ensure

Figure 4.2: Left and Right Eye View for the virtual Hole-in-Card Test: Participant's view during the task. The left panel displays the left eye's -, and the right panel shows the right eye's view of the yellow target. The grey card is attached to the cursor held by the participant. In this instance, the participant used their right eye to align the cursor with the target, indicating right-eye dominance during the trial.

they remained out of reach. The target's angular size of 3.2423° corresponded to a 3 cm perceived size in the visual field. Alignment was automatically verified after maintaining successful alignment for 100 consecutive frames. If alignment was interrupted, the counter reset. Figure 4.2 shows the left and right eyes' view of a participant after successful alignment.

4.2.1 Summary of testing methods

In both the hole-in-card and point test, the test results depend on the participant indicating alignment with a distant target. Ideally, participants can make a clear distinction between both eyes in these tests. Nevertheless, a limitation of these two methods is their subjective nature. Ambiguous results may occur when participants indicate the target is well-aligned with either eye. Here, it is possible that they either adjust their posture to re-align the finger or card with the target. In turn, the Miles test relies on the experimenter, who can note with which eye a participant has aligned the target. Again, small shifts in posture and anatomy, such as small IPD, can make determining the dominant eye cumbersome. With the in-HMD method, such small postural adjustments in posture are prevented by participants being required to keep the eye, cursor, and target aligned. It also does not require any intervention from an experimenter (or manual reporting in general). Thus, this method could be added as an additional (even invisible) step during the eye tracking calibration or on-boarding. For example, a dwell-based confirmation could start or end the eye-tracking calibration.

4.3 Study

All experiments reported in this and the following two chapters (Chapters 5 and 6) were conducted within a single data collection session, using the same participants. The order of the three separate experiments was counterbalanced across participants to control for potential order effects. The total study duration across all experiments was 45 minutes on average, with a maximum of 60 minutes.

As part of a larger study, we tested participants' eye dominance using the three most commonly used tests: Miles-, hole-in-card-, and point test. Each participant completed each test once, which lasted around 10 minutes in total. All tests, except for the in-HMD method, were performed using both hands to eliminate any potential hand bias in the results. Since it is uncommon to hold a VR controller with both hands, we opted to test it with one hand at a time. To examine the effects of handedness, each participant completed the test twice — once using the left hand and once using the right hand.

4.3.1 Procedure

Before participation, subjects signed informed consent and completed a demographics questionnaire. A *Edinburgh Handedness Inventory* [95] test was completed by each participant at the end of the study. The questionnaire determines the strength of handedness, allowing for a more defined understanding of participants' handedness. Then, subjects completed each eye dominance test as instructed. Participants completed the three traditional tests in order (Miles, hole-in-card, point test). First, eye dominance was tested with the *Miles-test*, using a triangle with both thumbs and index fingers. The *hole-in-card test* was conducted using a 10×10cm card containing a 2.5cm diameter hole in the center. While aligning the card at head height, subjects then viewed a 3m distant target through the hole of the card. For the *Point test*, participants pointed at a 3m distant target with both index fingers, shaping their hands like a gun (hands clasped). Finally, as part of the main experiment, participants aligned the virtual card with a virtual target.

4.3.2 Apparatus and Participants

The VR test was presented in VR developed with the SteamVR toolkit in Unity 2022.3.15 on a computer with an Intel Core i7-12700KF CPU, 32 GB RAM, and an NVIDIA GeForce RTX 4070 GPU. We used an HTC VIVE Pro Eye VR headset for the study, with 110° diagonal FOV, 2880×1600 pixels resolution, and 90 Hz refresh rate.

The study involved 28 participants (11 female, 16 male, 1 non-binary; M = 29.12 years, SD = 8.02; age range: 20–48) recruited from our local university. Seventeen participants reported normal vision, while 11 had corrected-to-normal vision (using contact lenses to avoid discomfort with large eyeglass frames in the HMD). Most participants (26) were right-handed, with one left-handed and one ambidextrous, as determined by the Edinburgh Handedness Inventory. Participants received £10 as compensation. The university's ethics committee approved the study.

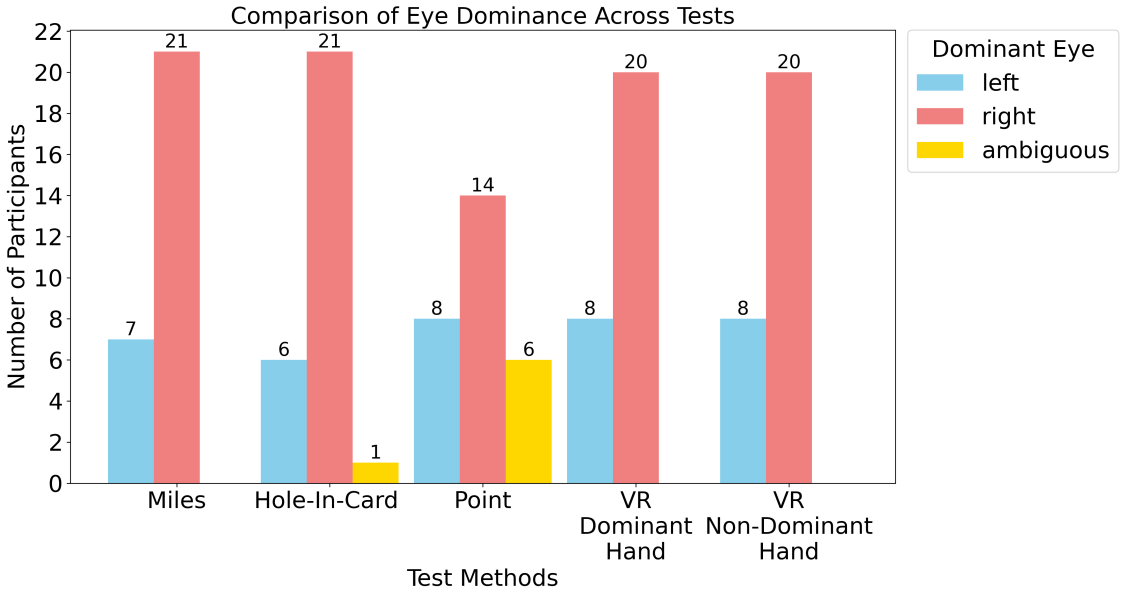


Figure 4.3: Number of participants classified as left dominant, right dominant, or ambiguous across five eye dominance testing methods. The results demonstrate variability in classifications, highlighting potential inconsistencies between test methods.

4.4 Results

Figure 4.3 illustrates the cumulative sum of all tests. Overall, the eye dominance testing methods yielded inconsistent results, as indicated by the different amount of people classified as left-eye dominant, right-eye dominant, and ambiguous per test. While general trends exist (more right than left eye dominant participants), only the hole-in-card test and the point test led to participants being classified as ambiguous (note this happened when it was unclear which eye was used for alignment, e.g., due to participant repeatedly shifting posture). Looking at all results, no two tests agree (or disagree), except the two in-VR tests. The point test is a strong outlier, having 6 participants classified as ambiguous. Looking at test results per participant, Figure 4.4 shows the distribution of left-, right-eye dominant and ambiguous participants. Only participants 12, 23, and 25 displayed true disagreements, with more than two tests disagreeing. For all other non-agreeing tests, only one test does not agree (Participants 4, 9, 11, 14, and 17). For two participants (12 and 23), the in-VR tests disagree (one says left- and the other says right-eye dominant). These two participants are also the only two where the Point test disagrees with the majority and does not say ambiguous but left-eye dominant. For all other tests, the in-VR tests agree with each other and the majority value of the traditional tests.

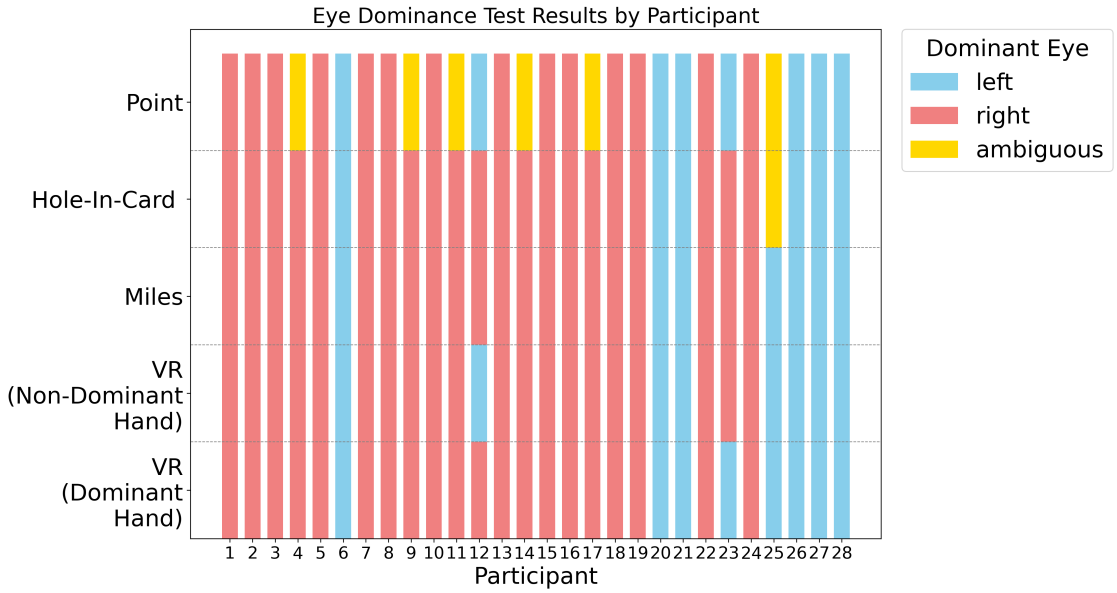


Figure 4.4: Eye dominance test results per participant of five eye dominance testing methods. The point test shows most inconsistencies due to many classifications as "ambiguous". Note: Participant 3 is left-handed, and participant 10 is ambidextrous.

4.5 Discussion

Our results reveal inconsistencies across eye dominance tests, with varying classifications as left-eye dominant, right-eye dominant, or ambiguous. Our findings indicate that traditional tests frequently disagree (9 out of 28 cases), with the point test being the most divergent (8 out of 9 cases). In contrast, our in-HMD method shows a high level of agreement with both the Miles test (26 out of 28 cases) and the Hole-in-Card test (25 out of 28 cases) and aligns with the majority consensus of the three traditional tests in most instances (25 out of 28 cases). The two in-VR tests almost always agreed with each other (26 out of 28 cases) and most traditional test outcomes. The hole-in-card and point tests were the only methods to classify participants as ambiguous, often due to unclear alignment. Notably, two participants (12, 23) disagreed within the in-VR tests (dominant- vs non-dominant hand), highlighting potential issues with traditional and point-based methods while supporting the reliability of in-VR testing.

4.5.1 Possible Reasons for Inconsistencies

The point test requires participants to point themselves and alternately close one eye. Participants might subconsciously adjust their fingers or upper body to align with the target while keeping one eye closed. In addition, different anatomies (e.g., IPD, arm length) might prevent a correct singular alignment (as in: the target is

close to being aligned with both eyes). The point test is also the only test that does not require participants to look "through" something (hole in a card, triangle formed by hands), thus making it more susceptible to the parallax effect (double images). This could have irritated participants but also led to them aligning the target "between the two ghost images". While the parallax effect could also influence the results of the Miles test or the hole-in-card test, the material surrounding the hole participants look through minimizes this effect. Despite thorough explanations, the point tests appear inherently susceptible to inaccuracies, as indicated by the high number of ambiguous cases.

Interestingly, all traditional tests are bi-manual and, thus, do not integrate the influence of the hand used for alignment into their results. However, previous research has suggested that the hand used for interaction can influence which eye is dominant [27, 26, 14]. This might be the cause for the disagreement between the in-VR tests.

4.6 Chapter Summary

In this chapter, we investigated eye dominance in AR/VR by comparing three traditional tests and introducing an in-HMD test, the Virtual Hole-in-Card Test. Our results showed that traditional tests often disagreed, with the point test deviating the most. In contrast, the in-HMD test demonstrated strong alignment with the Miles and Hole-in-Card tests, and generally agreed with the majority consensus of the traditional methods. These findings emphasize the need for multiple tests to establish eye dominance and suggest the in-HMD test as a valid alternative for AR/VR applications. This work provides practical insights for researchers and practitioners by streamlining eye-dominance testing, simplifying the calibration process, and supporting the development of eye-dominance-based technologies.

Chapter 5

Effects of Viewing Angle, Handedness and Eye Movement on Eye Dominance

As seen in the previous study (Chapter 3), we confirmed the dynamic nature of eye dominance to also apply within VR settings. Horizontal viewing angle and handedness were contextual factors that influenced which eye was dominant at a given moment. Target distance did not have a significant effect on which eye was dominant. However, the previous study explored the behavior using static targets only. Similarly, standard eye dominance testing procedures rely on stationary targets. Given the context of immersive 3D environments such as VR, content may be presented dynamically. In light of this, previous work on static targets must be extended to dynamic settings to leverage eye dominance in AR/VR, where users interact with static and dynamic targets that elicit distinct eye movements. Thus, this chapter examines target behaviors by eliciting different eye movements: random saccades, sequenced saccades, and smooth pursuit, addressing **RQ 2b**. With this, we provide insights into additional factors influencing eye dominance (viewing angle, hand used during interaction, and gaze behavior) and offer means to strengthen eye-dominance-based work in HCI further. To further explore these factors, we used our adapted in-HMD testing method as presented in Chapter 4 to accommodate moving targets and still avoid reliance on participant reporting. This strengthens previous findings in static scenarios and extends them to dynamic settings — essential for leveraging eye dominance in HCI and AR/VR.

5.1 Study

This study explores eye dominance by examining how target and gaze behavior influence eye dominance in alignment tasks. Participants completed three VR alignment tasks. In each task, participants aligned a virtual cursor and target with

their line of sight, requiring them to choose one eye, defined as the dominant eye, based on sighting dominance. The tasks are:

1. Alignment of the cursor with the target at pseudo-random horizontal positions, inducing random saccades.
2. Alignment of the cursor with targets presented in horizontal sequence, inducing sequenced saccades.
3. Alignment of the cursor with dynamic horizontally moving targets, inducing pursuit movements.

5.1.1 Task

5.1.1.1 Task 1: Random Saccades

This task explored eye dominance behaviors across various horizontal viewing angles, focusing on which eye participants use for alignment. For task 1, we used the same task and dominant eye classification procedure (virtual Hole-in-card test) as in Chapter 4.

See Figure 4.2 (Chapter 4) for the visualization of the setup: a virtual round target and a rectangular card (10×10cm) with a dynamic 3.2423° sized central hole, attached to the controller. This design mimicked the traditional hole-in-card method. Participants viewed the target through the hole while aligning the target, cursor, and one eye (e.g., right eye in Figure 4.2). The card forces people to precisely align one eye with the target, mitigating parallax issues.

Khan and Crawford placed targets with a diameter of 3cm at a 0.53cm distance from participants. We placed targets at 2m to ensure a parallax effect and out-of-reach placement. The target's 3.2423° size was perceived as 3cm in the visual field. Alignment was confirmed automatically after 100 consecutive frames of successful alignment. If participants broke alignment, the counter restarted. After confirmation, the target disappeared and reappeared at a new location. The locations of targets were repeated twice and presented randomly at angles from -30° to 30° at 2.5° increments along the horizon. Targets remained anchored to the head-mounted display (HMD) to ensure stable viewing angles, countering participants' head movements without requiring a chin rest. Participants were asked to remain seated and face forward. This procedure was repeated for both dominant and non-dominant hand alignment.

Together, we measured the eye used during alignment and had the following independent variables :

- Target angle: -30° to +30° in 2.5° intervals
- Hand used during alignment: dominant, non-dominant

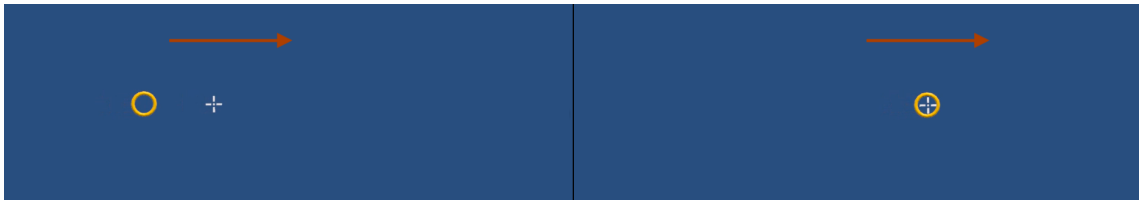


Figure 5.1: Left and Right Eye View in Task 3 – Pursuit Movement. The left panel displays the left eye's perspective, and the right panel shows the right eye's view. The yellow ring is the moving target, while the arrow indicates the direction of movement from left to right. The crosshair is the cursor controlled by the participant. In this instance, the participant used their right eye to align the cursor with the moving target, indicating right-eye dominance during the task.

5.1.1.2 Task 2: Sequenced Saccade

Task 2 explored whether previous target locations influence a switch in eye dominance by eliciting a sequence of saccades. It has a similar visual layout as Task 1 (target size, target distance, card-with-hole, HMD-fixation of targets) but differs in the order in which the targets were presented.

The first target appeared at the outermost angle (-30° or 30°, depending on movement direction) and was termed the *reference target*. The next target appeared 2.5° closer to the opposite side, termed the *intermediate target*. The sequence alternated back to the reference target and continued this pattern, gradually moving to the opposite side while maintaining consistent spacing. This sequence continued until the final target appeared on the opposite side of the reference target. The procedure was repeated twice for each hand (dominant and non-dominant) and movement direction (left, right).

This task examines whether participants switch eyes when moving from the reference target to the intermediate target. The independent variables were:

- Target angle: -30° to +30° in 2.5° intervals.
- Hand used during alignment: dominant, non-dominant
- Sequence direction: left-to-right, right-to-left

5.1.1.3 Task 3: Pursuit Eye Movements

Figure 5.1 shows the task layout. This task examined dominant eye behavior during pursuit eye movements and whether participants switched eye dominance. Participants aligned a virtual cursor (white crosshair) with a target (yellow ring, size 3.2423° in visual angle), moving at a constant speed (6.5°/second) across the horizon. The crosshair replaced the hole-in-card because the card obstructed the target if alignment was lost, making realignment difficult. The target movement range started from -30° to +30° and vice versa, depending on movement direction

and was HMD-fixed, as in tasks 1 and 2. A trial only began after successful alignment for 100 consecutive frames.

We studied if participants switched the eye used for alignment during the movement with the following independent variables:

- Hand used during alignment: dominant, non-dominant
- Target direction: left-to-right, right-to-left

5.1.2 Apparatus and Participants

Identical apparatus and participant sample as in the previous study were used. The study tasks were presented in VR developed with the SteamVR toolkit in Unity 2022.3.15 on a computer with an Intel Core i7-12700KF CPU, 32 GB RAM, and an NVIDIA GeForce RTX 4070 GPU. We used an HTC VIVE Pro Eye VR headset for the study, with 110° diagonal FOV, 2880×1600 pixels resolution, and 90 Hz refresh rate.

A total of 28 participants (11 female, 16 male, 1 non-binary, M=29.12 SD=8.02 years, age range: 20-48), recruited from our local university, participated. Seventeen reported normal vision, and 11 had corrected vision (ensuring participants wore lenses to avoid discomfort in the HMD resulting from large frames). Most participants (26) were right-handed, with one left-handed and one ambidextrous, per the Edinburgh Handedness Inventory. Three eye dominance tests showed inconsistent results (majority right-eye dominant; see Table 5.1). Participants received £10 compensation. The university's ethics committee approved the study.

5.1.3 Determining Eye Dominance

To determine the dominant eye, we used our in-HMD method described and evaluated in Chapter 4. Figure 4.1 (Chapter 4) illustrates how eye dominance was determined using a geometric measurement without relying on hand movement after alignment within a trial. The center of the left and right eyes are represented by LE and RE, respectively. C represents the center of the cursor in VR (either the cross-hair or the hole-in-card center, depending on the task), and T indicates the center of the target. We used vectors from each eye's center through C ($\overrightarrow{RE\ C}$ and $\overrightarrow{LE\ C}$) for the calculation. A reference line parallel to $\overrightarrow{LE\ RE}$, passing through the target center (T), intersects with these vectors. We then measured the distances between the T and the intersection points A and B. The dominant eye was identified as the one corresponding to the shorter distance, either $\overrightarrow{A\ T}$ or $\overrightarrow{B\ T}$.

We measured the IPD to ensure accurate eye positions by photographing participants holding an 85mm card at eye level. A digital photo-editing tool (GIMP) was used to measure the number of pixels of the card length and of the IPD (from pupil

Method	Right Eyed	Left Eyed	Ambiguous/Equal
Miles Test	21 (75%)	7 (25%)	0
Hole-in-card Test	21 (75%)	6 (21%)	1 (4%)
Point Test	14 (50%)	8 (29%)	6 (21%)

Table 5.1: Results of standard eye dominance tests across participants.

to pupil). Using these values, the IPD was calculated with the formula:

$$IPD = \frac{85mm}{\text{Card } pixels} \times \text{IPD } pixels$$

The IPD and the HMD's position were combined to determine accurate eye positions, counter eye tracking inaccuracies, and ensure stable, consistent calculations during the experiments. Note that this study relies solely on positional data reported from the headset, the IPD, and the controller without the need for eye-tracking.

5.1.4 Procedure

Before participation, participants signed informed consent and completed a demographics questionnaire. IPD was measured, and tasks were explained. The HMD was adjusted by rotating the IPD knob to match the IPD. As part of the larger data collection, this individual experiment took an average of 10 minutes to complete.

To control for order effects, *task* order was randomized, and a 4×4 Latin square design was used for balanced condition presentation. After the experiment, we asked participants to complete the *Edinburgh Handedness Inventory* [95] to assess handedness strength.

5.2 Results

We did not drop any data due to eye tracking. For tasks 1 and 2, we considered the last 30 out of the 100 frames to determine the eye used for alignment and calculated the mode (majority value). For task 3, no such calculation was possible, but switches in eye dominance were recorded. In tasks 1 and 2, we consider a single trial a saccade between two targets (the reference and intermediate target). A switch occurred if participants used a different eye to align the reference and intermediate target. In task 3, a switch is considered when the eye used for alignment changes during the pursuit movement.

5.2.1 Task 1: Random Saccades

Task 1 examined whether and how the eye used to align a virtual target depends on different horizontal viewing angles during random saccades. Furthermore, the

Table 5.2: Task 1 – Binomial Logistic Regression. No independent variable was a significant predictor.

Variables in the Equation	B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I. for Exp(B) Lower	Upper
Hand used for alignment	0.153	0.085	3.246	1	0.072	1.166	0.987	1.378
Horizontal target angle	0.001	0.002	0.269	1	0.604	1.001	0.997	1.006
Constant	0.909	0.059	235.773	1	<.001	2.483		

task explored the influence of the hand that was used for alignment. Each of the 15 angles was visited four times in total, twice using each hand.

5.2.1.1 Influence of Hand and Target Angle

A binomial logistic regression was fitted to determine the effects of hand use and horizontal viewing angle on participants' likelihood of using the right eye. Table 5.2 shows the results. The logistic regression model was not statistically significant, $\chi^2(2) = 3.518$, $p = .172$. The explained variation in the dependent variable based on our model ranges from 0.1% to 0.2%. The area under the ROC curve was .522 (95% CI, .498 to .546), which is a poor level of discrimination according to Hosmer et al. [49]. The binomial logistic regression model failed to find significant evidence that the predictors (hand used for alignment and horizontal viewing angle) reliably influence which eye a participant would use. This suggests that neither the hand used for alignment nor the horizontal target angle confidently predicted if a participant would use the right eye (or the left eye) in our task with random saccades.

5.2.1.2 Eye used during alignment

Figure 5.2 illustrates the distribution of left- and right-eye usage during alignment at every horizontal target angle of all participants, irrespective of which hand is used. Across all angles, the right eye is used more often than the left when aligning a virtual card and target, with the right eye being used 72.81% of the time.

5.2.1.3 Change in Eye Usage per Angle

Each angle was visited four times to examine consistency in eye use for alignment. Figure 5.3 shows the eye used by participants for each angle, split by hand. Most participants used the right eye, with 89 discrepancies observed across two repetitions: 35 (5.01%) with the dominant hand and 54 (7.76%) with the non-dominant hand. While hand use is not a significant predictor, Figure 5.3a and Figure 5.3b show salient differences in which eye participants use for alignment. Some participants consistently use their right eye (e.g., P7) or left eye (P25), and others showed very inconsistent behavior (P21) or specific patterns (e.g., the influence of angle, P1). Some switched eyes depending on the hand used (P6, P13). Right eye alignment occurred in 74.32% of dominant hand trials and 71.23% of non-dominant hand trials.

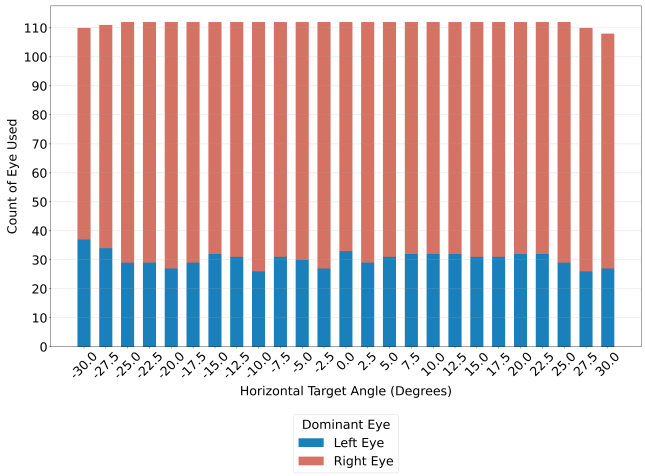


Figure 5.2: Task 1 – Distribution of left and right eye alignment across horizontal target angles for all participants, aggregated across both hands used. 112 trials were possible at every angle, but fewer trials were conducted at -30°, -27.5°, 27.5°, and 30° due to participants not seeing the target (it was at the edges of the field of view).

5.2.2 Task 2: Sequenced Saccades

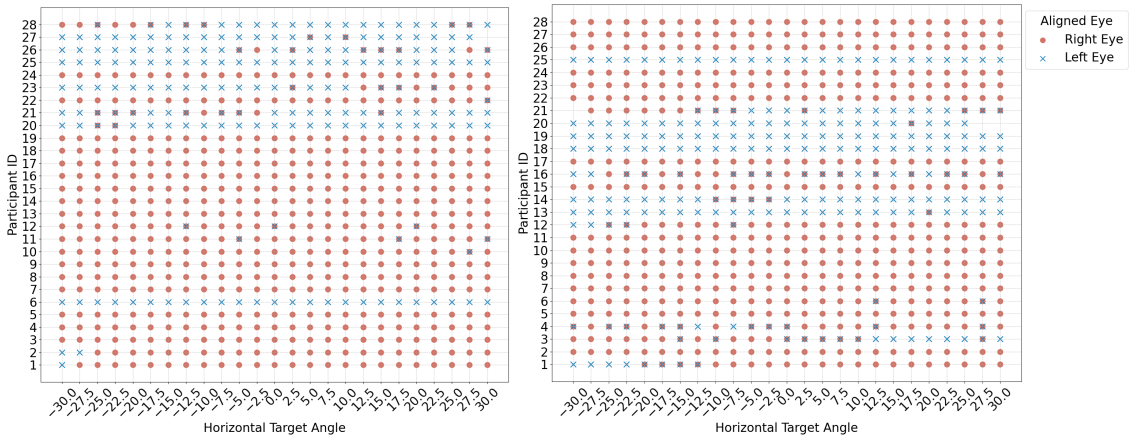
Task 2 investigated changes in eye alignment across horizontal angles, starting from the outermost angle based on movement direction, and whether the hand used for alignment and target angle predicted eye use during directed saccade sequences, unlike random saccades in Task 1.

5.2.2.1 Influence of Hand, Target Angle, and Movement Direction

We ran a binomial logistic regression to determine the effects of target sequence direction, hand used, and horizontal viewing angle on the likelihood of using the right eye for alignment. Table 5.3 shows the results. The logistic regression model was statistically significant, $\chi^2(3) = 90.388$, $p < .001$. Movement direction did contribute significantly to the model ($p < .001$). The explained variation in the dependent variable based on our model ranges from 0.8% to 1.2%. The area under the ROC curve was .556, 95% CI (.544, .568), which is a poor level of discrimination, according to Hosmer et al. [49]. These results indicate that a rightward movement direction of the sequence is associated with the likelihood of using the right eye during an alignment task. Still, while rightward movement direction is significantly associated with right-eye usage, the overall predictive capacity of the model is weak.

5.2.2.2 Eye used during alignment

Figure 5.4 illustrates which eye participants use during the final alignment at the target. Across all trials, the right eye was used in 70.62% of trials for the left-to-right direction and 78.46% trials for the right-to-left direction. Vice versa, the left



(a) Dominant Hand Used During Align-(b) Non-dominant Hand Used During Alignment ment

Figure 5.3: Task 1 – Eye used for alignment over target angle for all trials per participant. Every icon covers 2 trials. ● shows the right eye has been used in the two trials. × shows the left has been used. ⊗ means there was no consistent usage.

Table 5.3: Task 2 – Binomial Logistic Regression. Movement direction of the sequence predicts if participants use the right eye.

Variables in the Equation	**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B)**	**95% C.I. for Exp(B)**	
							Lower	**Upper**
Hand used for alignment	-.061	0.043	1.971	1	.160	.941	.865	1.024
Movement Direction	-.336	.053	39.535	1	**<.001**	.714	.643	.793
Horizontal target angle	0.002	.001	3.845	1	0.050	1.002	1.000	1.004
Constant	1.150	.042	761.978	1	<.001	2.483		

Note: Eye dominance is for right-eyed, compared to left.

eye was used in 29.38% of trials for the left-to-right direction and 21.54% for the right-to-left direction.

5.2.2.3 Eye dominance shift location

Of all 5341 analyzed trials, 283 trials (5.29%) from 16 participants resulted in a switch. Of those, 130 (45.94%) led to a switch for left-to-right sequences and 153 (54.06%) in right-to-left sequences. Participants switch the eye they use for alignment at an average angle of -7.61° (SD=16.37) for targets starting right and moving left and at an average angle of 7.29° (SD=15.66) for targets starting left and moving right, regardless which hand was used. The average angle across all conditions is -0.77° (SD = 17.66). Table 5.4 shows these switches' mean horizontal angles by dominant hand and movement direction. Figure 5.5 illustrates how often and where participants switched eyes over the target angle and movement direction. The farther the target is from the start, the more switches we observe.

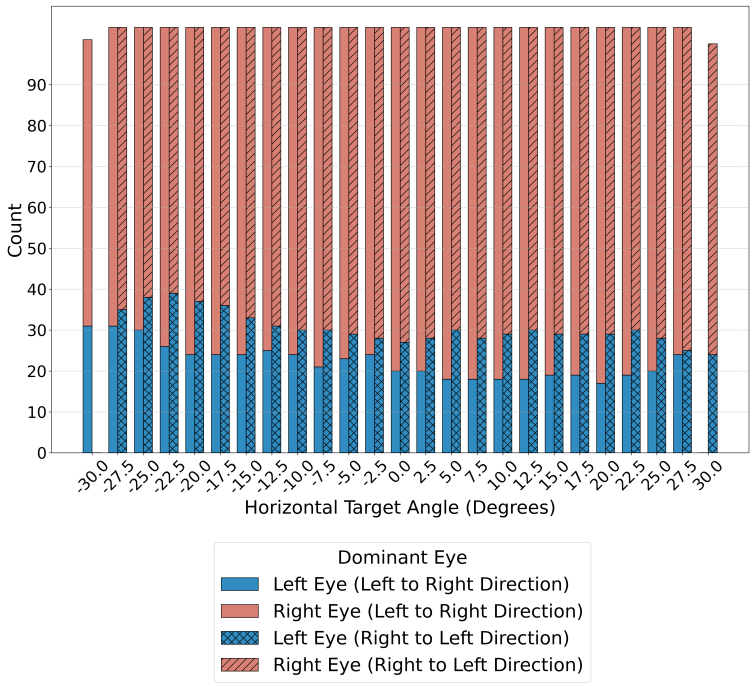


Figure 5.4: Task 2 – Distribution of left and right eye alignment by target angles, split by target sequence direction. Each angle and direction had a potential of 104 trials, though fewer trials were conducted at -30° and 30° due to visibility constraints.

5.2.3 Task 3: Eye Dominance in Pursuit Movements

Task 3 investigated eye dominance and switches during pursuit eye movements. Task 3 modifies task 2 by introducing continuous target movement (left-to-right and right-to-left movement direction), resulting in pursuit eye movements.

5.2.3.1 Influence of Movement Direction and Hand

A binomial logistic regression determined the effects of hand used for alignment, target movement direction and horizontal target angles on the likelihood of aligning with the right eye, presented in Table 5.5. The model was statistically significant, $\chi^2(3) = 2656.51, p =< .001$). All independent variables contribute significantly to the model ($p < .001$). The explained variation in the dependent variable based on our model ranges from 1.4% to 2.1 %. The area under the ROC curve was .577, 95% CI (.574, .580), which is a poor level of discrimination, according to Hosmer et al. [49]. Within the context, the hand used during alignment, target movement direction, and horizontal target angle could — albeit poorly — predict whether a participant aligns the target with the right eye.

Table 5.4: Task 2 – Average angle at which a switch in eye usage occurred, by hand used for alignment and sequential target movement direction. Rightward movements show larger switch angles than leftward movements.

Hand Used	**Movement Direction**	**Switch Angle M (SD) [°]**	**N**
Dominant	Left	-6.54 (17.00)	73
Dominant	Right	7.21 (15.41)	61
Non-Dominant	Left	-8.59 (15.59)	80
Non-Dominant	Right	7.36 (15.88)	69

Table 5.5: Task 3 – Binomial Logistic Regression Task. Hand used for alignment, movement direction and horizontal target angle predicts if participants use the right eye.

Variables in the Equation	**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B)**	**95% C.I. for Exp(B)**	
							Lower	**Upper**
Hand used for alignment	.183	0.011	294.788	1	**<.001**	1.202	1.176	1.226
Target Movement Direction	-.379	.011	1257.230	1	**<.001**	.685	.670	.699
Horizontal Target Angle	.010	.000	1100.705	1	**<.001**	1.010	1.010	1.011
Constant	1.161	.009	125295.081	1	<.001	3.193		

Note: Eye dominance is for right-eyed, compared to left.

5.2.3.2 Eye used during alignment

In total, we observed a switch in 47 of 224 trials. These switches, or reversals of eye usage, were either permanent or not. Figure 5.6 illustrates representative examples of switches during pursuit movements. A *non-permanent* switch occurred in 15 of the 224 trials (6.69%). In these trials, participants switched their eyes temporarily. Six trials happened with the dominant hand and 9 with the non-dominant hand. Figure 5.6a illustrates such a trial. A *permanent* switch in eye dominance during pursuit alignment tasks occurred in 32 (14.29%) instances across all 224 trials. Figure 5.6b illustrates a permanent switch in eye dominance. Of these cases, 14 (43.75%) trials were performed with the non-dominant hand. The remaining 177 (79.02%) trials presented consistent eye usage (cf. Figure 5.6c).

5.2.3.3 Eye dominance shift location

Of the trials displaying switches, whether temporary or permanent, the average horizontal angle where the switch happened was at -5.77° (SD = 19.77) For permanent switches, the average angle was -7.51° (SD = 18.14). It was -1.05°(SD = 22.75) for non-permanent switches. Table 5.6 lists the mean horizontal angles at which eye dominance switches occurred, grouped by hand used for alignment and movement direction. Left-to-right switch angles are directed slightly closer toward the center than right-to-left angles.

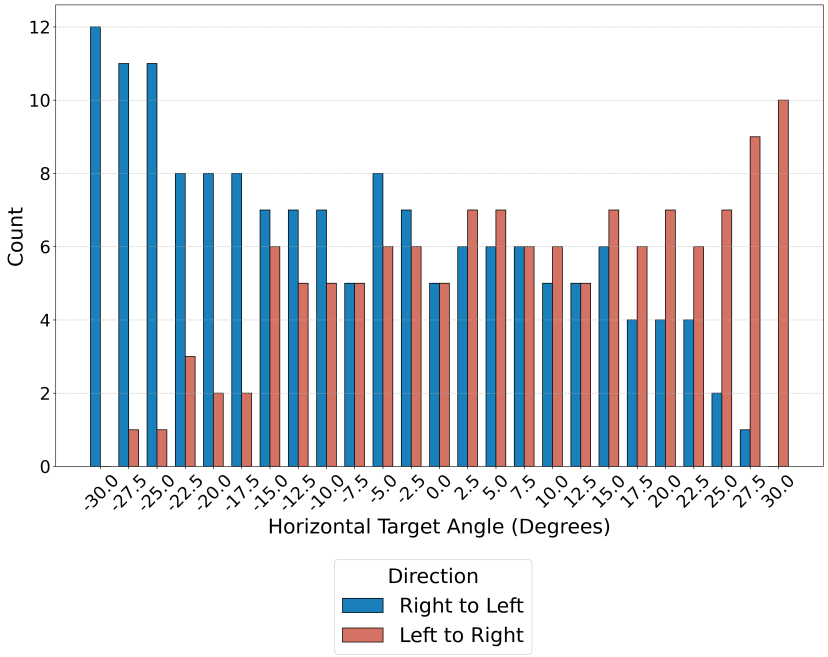


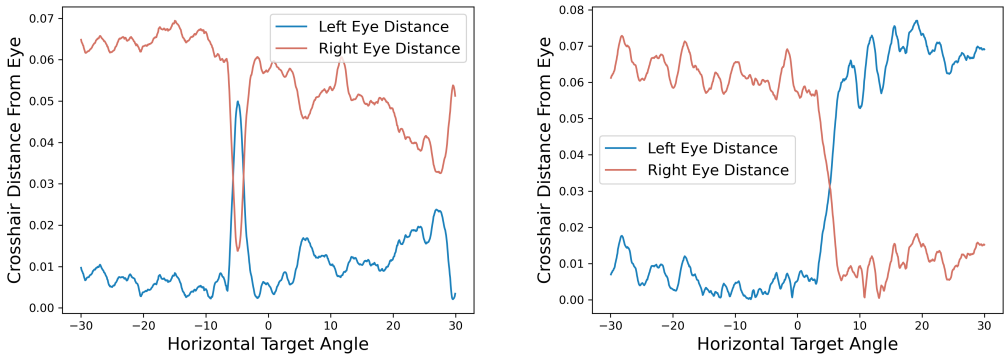
Figure 5.5: Task 2 – Counts of switches across all participants over a horizontal viewing angle, split by movement direction. The farther away the target angle is from the start angle, the more switches we observe.

5.3 Discussion

This work advances the fundamental understanding of eye dominance in HCI by examining how target and gaze behavior influence eye dominance in alignment tasks. We analyzed whether and how the eye used for alignment changes between two consecutive trials. Participants completed three tasks to induce different eye movements — random saccades, sequenced saccades, and smooth pursuits — while we analyzed changes in eye usage across trials, considering factors like horizontal viewing angle, hand used for alignment, and target movement.

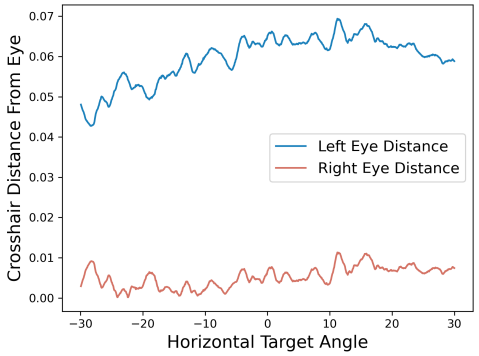
Table 5.6: Task 3 – Average angle at which a switch in eye usage occurred, by hand used for alignment and target movement direction. Right-to-left movements show larger switch angles than left-to-right movements.

Hand Used	**Target Movement Direction**	**Switch Angle M (SD) [°]**
Dominant	Left-to-Right	-3.34 (19.22)
Dominant	Right-to-Left	-13.39 (14.76)
Non-Dominant	Left-to-Right	-2.88 (24.73)
Non-Dominant	Right-to-Left	-16.96 (4.11)



(a)

(b)



(c)

Figure 5.6: Task 3 – Single Trial Pursuit Data. a) Changes of eye usage between -10 and 0°, yet trial starts and ends with left eye usage. b) Trial starts with left eye usage and changes to right between 0 and 10°. c) A single trial with consistent right-eye usage.

Results support the dynamic nature of eye dominance but also draw a more nuanced picture with less pronounced effects than prior research. Overall, we found that, while eye dominance does change for some participants, it is less dynamic than suggested by previous research. Across all tasks, participants exhibited few switches in eye dominance, measured via a change in the eye used during alignment. Regarding influential factors, neither angle nor hand used for alignment significantly affected random saccades. For sequenced saccades, only sequence direction had an effect; the hand used for alignment did not. The hand used for alignment, target movement direction, and target angle showed an effect for pursuit movements.

5.3.1 Relation to Previous Results

The results of our study conflict with previous findings and results of our first study, where eye dominance (the eye used for alignment) is predicted by horizontal viewing

angle [59]. In our work, the target angle does not predict eye dominance for random or sequenced saccades. A core difference between previous studies and ours is the smaller angle range in which we presented targets. When starting trials at the outermost angles, participants were most likely required to choose only one eye, as the other eye is unlikely to view the target. This makes switches in eye dominance throughout tasks more likely, particularly when gaze shifts increase in size (especially with VR-HMDs). In light of this, we assume that viewing angle, especially closer to the periphery, predicts eye dominance. The key takeaway is that eye dominance is dynamic and influenced by horizontal viewing angles, albeit less so when the range for random saccades is small.

Another difference is that the method used to determine eye dominance might influence the results. In our previous study (Chapter 3) and prior work, participants had to move a controller and cursor or their hand [59] along their line of sight from the target to the eye they had used for alignment. This motion might have additional unknown influences on eye dominance that are not part of our metric, which is purely based on geometry during alignment.

5.3.2 Eye Used During Alignment and Switch Location

Approximately two-third of trials showed participants using their right eye for alignment, consistent with our sample (two-third reporting right-eye dominance). Despite all but one participant being right-handed, handedness had little influence on tasks 1 and 2. Only in the more complex task 3, involving continuous motor tracking, did the aligning hand weakly predict eye usage.

Temporary switching in task 3 may result from parallax, leading to double vision for some participants and follow-up realignment. Overall, results suggest that assuming a static dominant eye (e.g., post-calibration) is generally reliable. However, even strongly right-eye dominant participants occasionally switched to using the left eye and reverted. Such inconsistencies pose challenges for applications relying on stable eye dominance, potentially degrading user experience (e.g., by users detecting the lowered image quality in eye-dominance-based foveated rendering).

Similarly, the location of these switches varies greatly. For task 1, our previous results from Chapter 3 suggest crossovers at around 3° for the left hand and -7° – -10° for the right hand for random target angles (although with different target distances), aligning with results from task 2 but with less symmetry. In task 2 (sequenced saccades), the average switch angles are relatively symmetrical for movement directions (appr. ±7.5° from center). Notably, the type of eye movement seems to be especially important. In task 3 (pursuit), a pronounced leftwards bias emerged, especially for targets moving from right to left (appr. -15° vs. appr. -3°). Neglecting such dynamics risks degraded user experiences, for example, in applications like VR games that rely on eye dominance for accuracy. First-person shooters, for instance, may benefit from accommodating eye dominance switches by

relaxing assumptions of static eye dominance or symmetrical zones, especially in central and left-field regions.

5.3.3 Limitations and Future Work

This study faced limitations that inform future research. Hand tremors during alignment tasks may have impacted eye dominance accuracy, highlighting the need for hands-free or more robust methods. Additionally, task repetition might have led participants to rely less on eye dominance and more on behavioral cues like parallax and double vision. This suggests varied and sensitive task designs to capture eye behavior nuances. Furthermore, only using horizontal viewing angles may limit the generalizability of our findings. Future research could benefit from larger sample sizes and incorporating factors like visual acuity to account for variability.

For future work, a potential direction could be developing a structural equation model (SEM) to assess the multivariate nature of the problem. This would provide a deeper understanding of the relationships between factors influencing eye dominance, such as target angle, hand used, movement direction, target size, target depth, and cognitive load. By modeling these factors within a unified framework, SEM could reveal their interactions, enabling more targeted and practical understanding and personalized user interface adaptations.

5.4 Chapter Summary

This chapter investigated factors influencing eye dominance switches in HCI and VR, studying the influence of horizontal viewing angle, hand used for alignment, and target-induced eye movements in three alignment tasks. Our findings confirm the dynamic nature of eye dominance but reveal fewer switches than previously suggested. Key influencing factors vary across tasks and target behavior. Understanding the dynamic nature of eye dominance is crucial for optimizing user interface design, interaction, and rendering, particularly in AR/VR environments. Our study challenges the notion of eye dominance as a static, predictable trait, demonstrating its variability. These findings underscore the need for adaptive HCI systems that account for eye dominance fluctuations and incorporate calibration, improving accuracy and user experience in VR and AR environments. This work opens pathways for developing adaptive HCI systems that personalize interactions based on individual behaviors. Key takeaways include integrating dynamic eye dominance into real-time designs, considering task-specific shifts for out-of-reach selection or foveated rendering, and further exploring how task complexity and eye movement patterns can optimize immersive system designs.

Chapter 6

Effect of Vertical Angles on Eye Dominance

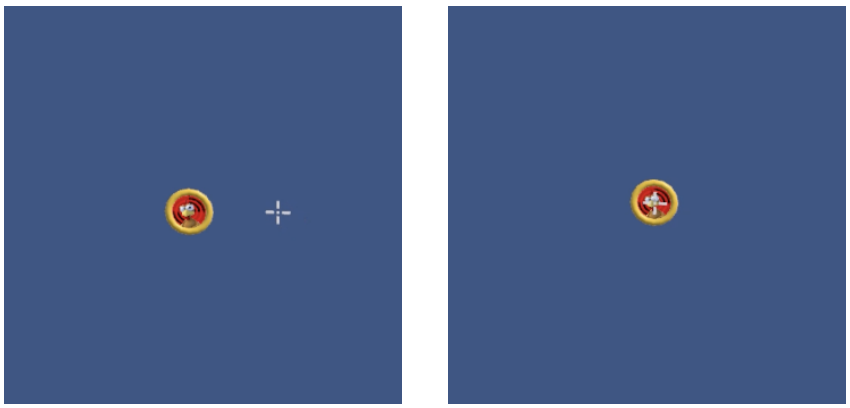
The previous chapters highlighted dynamic shifts of eye dominance in response to individual and contextual factors, such as horizontal viewing angle and target behavior (Chapters 3 and 5). However, interactions in virtual reality (VR) involve targets distributed across two dimensions, yet the role of vertical viewing angle on eye dominance remains unclear. In this chapter, we address **RQ 2b** by exploring the effect of the vertical dimension of target position on eye dominance and its switching behavior.

6.1 Data Collection of Eye Dominance During Visual Alignment

We conducted a laboratory study in which participants completed a perspective-pointing task in VR using a handheld controller. Alignment was a forced-choice.

6.1.1 Task

Participants performed a cursor-based pointing task in VR. A VR controller was held in one hand, with a crosshair cursor attached. Using the controller, subjects were required to rapidly point to virtual targets (cf. Figure 6.1). After successful alignment of the cursor with the target and maintaining alignment for 100 consecutive frames ($\approx$ 1.11 seconds), the target disappeared and reappeared at a new, pseudo-randomized location. A frame was considered aligned whenever the angle between the eye-target vector and eye-controller vector was below 2° (c.f Figure 6.2). A 2° threshold was chosen to ensure close alignment of eye, cursor, and target. In return, this forced participants to align the cursor and the target with a single eye.



(a) Left Eye View (b) Right Eye View

Figure 6.1: Left and Right Eye Task View. The yellow-red circle is the appearing target. The cursor (white cross) is controlled by the participant and aligned with the target. In this example, the crosshair is aligned with the right eye (b) and not with the left eye (a). Thus, we consider the right eye to be dominant.

Targets appeared randomly on a grid between -30° to 30° horizontally (stepsize: 6°) and -20° to 20° (stepsize: 4°) vertically. The grid size was chosen to balance experimental duration and cover the largest area of comfortable eye-in-head angles. Targets were fixed relative to participants' head-mounted display (HMD), ensuring the target position remained fixed, independent of head movement.

6.1.2 Procedure

Prior to participation, subjects signed informed consent and completed a demographics questionnaire. Then, the inter-pupillary distance (IPD) was measured and task procedure was clarified. Before data collection and whenever the HMD was removed during breaks, the eye tracker was (re-)calibrated for each participant individually. Participants then performed the alignment task.

The experiment was divided into four blocks of 25 targets each, resulting in 100 targets (alignment trials) per participant. After each block, participants had the option to take a short break. If the HMD was removed, it was recalibrated before commencing the next block of targets. This was repeated twice, once per hand (the hand in which participants held the controller), resulting in a total of 200 trials per participant. To control for order effects, we used a 2 × 2 Latin square to counterbalance order effects for the hand used during the trials. Half of the participants started the experiment using their dominant hand, whereas the other half started using their non-dominant hand. The average time to complete alignment within a single trial was 2.23 seconds (SD = .99 seconds). As part of the larger data collection study, using the same participant sample as for Chapters 4 and 5, this experiment lasted around 15 minutes per participant.

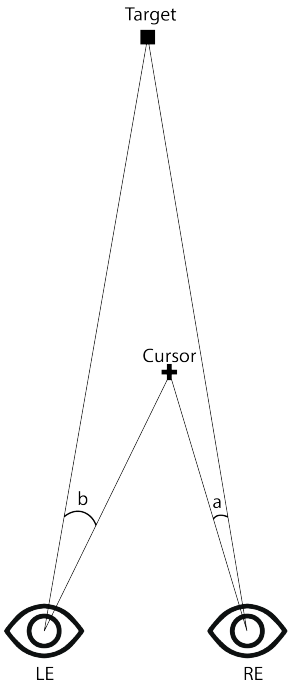


Figure 6.2: To ensure accurate alignment of the cursor, target, and the dominating eye, we calculated alignment vectors and compared the angular difference between these vectors. For acceptable alignment, either a or b < 2 °.

After the experiment, participants completed the *Edinburgh Handedness Inventory* [95]. This gave us a more nuanced understanding of participants' strength of handedness. Visual acuity was examined by means of the *Snellen test* [6]. Participants stood 6 meters from the Snellen chart in a well-lit room and were required to cover one eye. They were then required to read the Snellen letters out loud from top to bottom, and this was repeated for each eye and for both eyes open. Whenever participants incorrectly identified a letter, the experimenter noted the number of errors and the respective line in which they occurred. From this, the Snellen fractions for each eye and both eye trials were determined per participant. Table 6.1 presents the results of the Snellen test across participants. Additionally, participants indicated whether they have corrected vision in the demographics questionnaire. This assessment was independent of the visual acuity test, allowing us to assess vision at that specific moment. Notably, 8 participants who had self-reported normal vision showed worse-than-normal vision (below 20/20) on the Snellen test.

6.1.3 Apparatus and Participants

Although conducted as a separate task, this experiment used the same apparatus and participant sample as in the studies from Chapters 4 and 5. A total of 28 participants (11 female, 16 male, 1 non-binary, M=29.12, SD=8.02 years, age range:

Snellen Value	Left Eye	Right Eye	Combined Eyes
20/20	9 (32%)	8(28%)	14 (50%)
20/25	4 (14%)	5 (18%)	5(18%)
20/32	3 (11%)	6 (21%)	4(14%)
20/40	2 (7%)	4 (14%)	3 (11%)
20/50	5 (18%)	3 (11%)	1 (4%)
20/63	3 (11%)	2 (7%)	1 (4%)
20/80	1 (4%)	0	0
20/100	1 (4%)	0	0

Table 6.1: Results of the Snellen test for visual acuity across participants, ranging from normal vision (top) to moderate vision impairment (bottom). Note: For simplicity, letters missed are excluded from this table.

20-48), recruited from our local university, participated in the study. 17 participants reported normal vision, and 11 reported corrected-to-normal vision. We ensured participants with corrected vision wore lenses to avoid eye-tracking inaccuracies due to glasses. All but one participant indicated being right-handed. The Edinburgh Handedness Inventory results reported 26 right-handed participants, one left-handed participant, and one ambidextrous participant. After completing the study task, the three eye dominance tests yielded inconsistent results (cf. Table 5.1, Chapter 5).

The study task was presented in a VR environment developed with the SteamVR toolkit in Unity 2022.3.15 on a computer with an Intel Core i7-12700KF CPU, 32 GB RAM, and an NVIDIA GeForce RTX 4070 GPU. We used an HTC VIVE Pro Eye VR headset for the study, with 110° diagonal FOV, 2880×1600 pixels resolution, and 90 Hz refresh rate and a 120 Hz sample rate.

6.2 Results

6.2.1 Eye Dominance During Alignment

Due to tracking inaccuracies, 38 trials had to be discarded. On average, participants displayed 70.95% (SD = 35.54%) right eye dominance across all trials. Figure 6.3 presents the relative frequency of right-eye dominant trials for each individual participant. Fourteen participants (50%) displayed right-eye dominance in more than 95% of their trials, indicating strong dominance (P4, P5, P7, P8, P9, P10, P11, P12, P13, P15, P16, P17, P22, P27). Two participants (7%) showed distinct left-eye dominance (P6, P23), where left-eyed trials > 90%. Yet, no single participant demonstrated a 100% left- or right-eye dominance. Two participants almost displayed an equal split of left and right eye dominant trials (P14 50.5% left-eye dominance, P2 46.5% left-eye dominance).

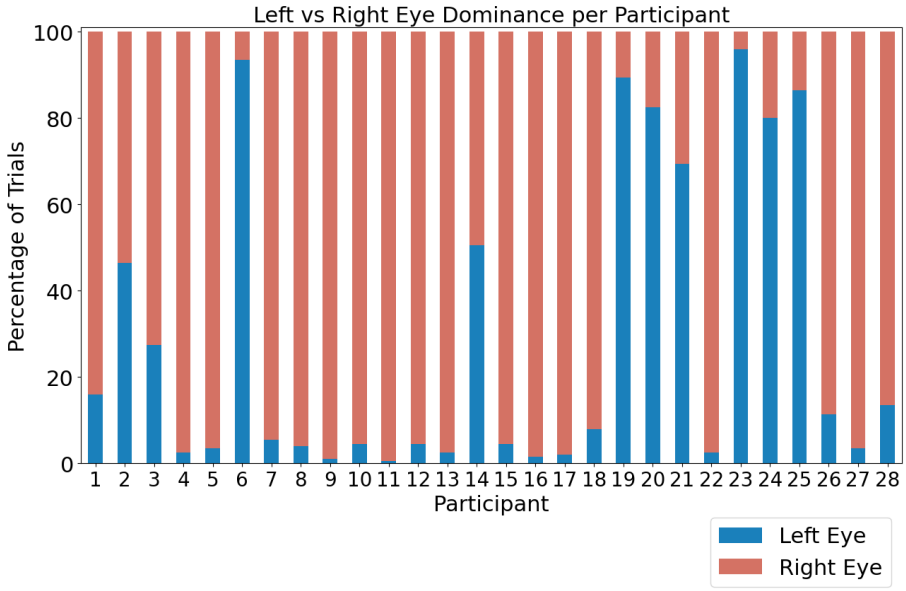


Figure 6.3: Right- vs. left-eye dominant trials across participants. Some individuals show strong eye dominance tendencies (high percentage left- or right-eye trials)(e.g., P6 vs. P4), whereas others show frequent switching (e.g., P14).

Table 6.2: Binomial Logistic Regression. Vertical target angle alone does not predict whether participants use the right eye.

Variables in the Equation	**B**	**S.E.**	**Z**	**Sig.**	**95% C.I. for Exp(B)**	
					Lower	**Upper**
Vertical Target Angle	0.0045	0.002	1.946	0.052	0.000033	0.009
Constant	0.9075	0.030	30.618	0.000	0.849	0.966

Note: Eye dominance is for right-eyed, compared to left.

6.2.2 Effect of Target Angle on Eye Dominance

Building on findings that horizontal target angle predicts right-eye dominance, we investigated whether vertical target angle does as well using a binomial logistic regression, as shown in Table 6.2. The model showed a negligible pseudo-R^2 (0.0006), indicating little explained variance. The coefficient for vertical angle did not reach significance ($p = 0.052$). Thus, there is only weak evidence that vertical target position alone predicts eye dominance.

Building on this, Table 6.3 includes both horizontal and vertical target angles and their interaction. A logistic regression including horizontal and vertical angles, as well as their interaction, significantly predicted right-eye dominance ($\chi^2(3) = 165.5, p < .001$, pseudo-$R^2 = .025$. Controlling for horizontal target angle, vertical target angle was not a significant predictor of right-eye dominance ($p = .198$). In contrast, horizontal target angle significantly predicted right-eye

Table 6.3: Combined Binomial Logistic Regression. Both horizontal target angle and the interaction horizontal × vertical target angles predict if participants use the right eye.

Variables in the Equation	B	S.E.	Z	Sig.	95% C.I. for Exp(B)	
					Lower	Upper
Vertical Target Angle	0.0031	0.002	1.288	0.198	-0.002	0.008
Horizontal Target Angle	0.0192	0.002	11.625	0.000	0.016	0.022
Interaction Horizontal and Vertical	-0.0006	0.000	-4.530	0.000	-0.001	-0.000
Constant	0.9381	0.030	30.802	0.000	0.878	0.998

Note: Eye dominance is for right-eyed, compared to left.

dominance ($p < .05$). The interaction between vertical and horizontal angles was also significant, indicating a negative interaction ($p < .05$). Thus, eye dominance during alignment tasks is primarily influenced by the horizontal location of the target, rather than its vertical location. However, vertical and horizontal target locations interact: when targets are presented at lower levels, the influence of horizontal position on dominance becomes stronger and vice versa.

Figure 6.4 displays the prevalence of right-eye dominance for each target position, across all participants and trials. Targets were presented consistently at a 2m distance and placed at diverse horizontal and vertical locations, forming a semi-cylindrical arrangement in front of participants. Displaying these 3D positions in a 2D plot (Figure 6.4) makes them appear curved. At lower vertical target positions, differences of right-eye prevalence between horizontal positions are most pronounced. The effect is strongest at the outermost angles. At -30° horizontal angle, most trials presented left-eye dominance, whereas at +30° right-eye dominance prevailed in most cases. This effect diminishes as targets are presented at higher vertical and more rightward positions.

6.3 Discussion

In this chapter, we explored the impact of target vertical and horizontal positioning on eye dominance. The horizontal angle emerges as the primary determinant, with its influence moderated by vertical position: effects are the strongest at lower vertical angles and converge as targets move upward. Taken together, these analyses show that eye dominance in the alignment task is not random but systematically related to target position.

These results align with those of our previous chapters, showing that changes in eye dominance respond to target positions. This highlights the need to incorporate the additional vertical dimension of target positions when testing or calibrating for eye dominance. Neglecting the vertical dimension could miss more frequent eye dominance switches, for example, during larger gaze shifts. A concrete example is

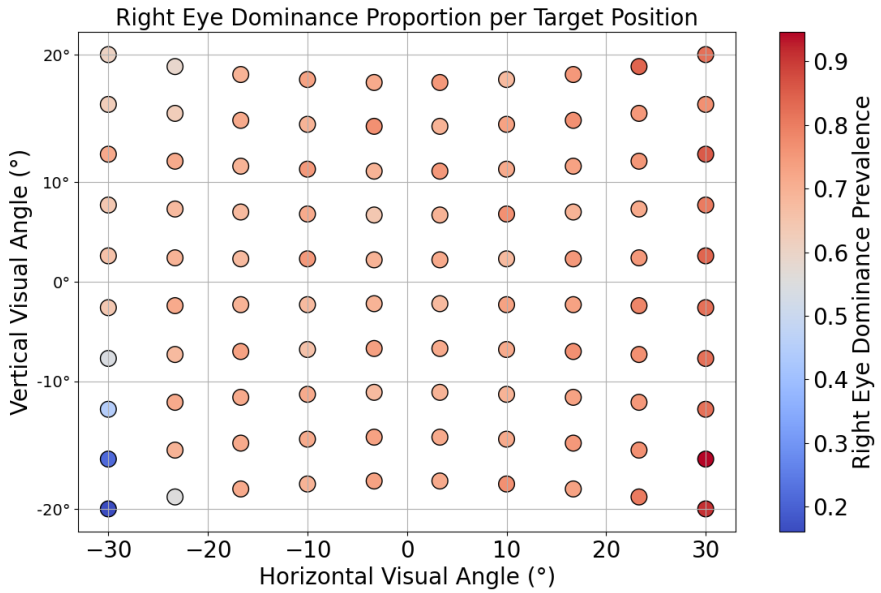


Figure 6.4: The relative prevalence of right-eye-dominant trials for each target location. The lower bounds (-20°) show a stronger horizontal effect on eye dominance. At left horizontal angles (-30°), more trials show left eye dominance, whereas at right horizontal angles, more trials display right eye dominance.

during desktop work, where gaze shifts on the vertical axis are common. Ignoring the more frequent eye dominance shifts on the lower vertical bound could bias calibration. This structure suggests that eye dominance can be modeled directly from spatial target features, enabling an automatic eye dominance detection. These patterns of eye dominance switches are systematic enough to enable predictive models that use the target position as a feature.

6.4 Chapter Summary

The study reported in this chapter provides further insight into the behavior and changes of eye dominance in interactive 3D environments. We explored the impact of the vertical dimension in isolation on eye dominance shifts, as well as the interaction of horizontal and vertical target locations. Our results show that the vertical angle of targets contributes to changes in eye dominance, especially at lower angles, where the effect of the horizontal angle is amplified. This highlights the need to incorporate the vertical position of targets into testing and modeling eye dominance behavior.

Chapter 7

Prediction of Eye Dominance in VR

Building on our work in the previous chapters, this chapter aimed to develop a machine learning model to automatically infer the dominant eye in users within interactive 3D contexts, addressing **RQ 3**. As our previous findings identified both contextual and individual factors that induce changes in eye dominance, we included these within our predictive models. We compared how models using only target-based features with those incorporating both contextual (target-based) and user-specific (individual) features influenced the prediction accuracy. To train our model, we used the raw data collected from the VR-alignment task in Chapter 6.

In 3D interaction, eye dominance biases the egocentric reference frame and visually guides the hand when pointing [9, 112, 126, 25]. While individuals point relative to their dominant eye, most XR systems assume eye dominance to be static [80]. Evidence from our previous chapters suggests otherwise, indicating dynamic and context-dependent shifts. This raises the question of how to capture such dynamics in practice. While some influencing factors have been identified, we still lack computational methods to infer which eye dominates at any given moment.

7.1 Classifying Eye Dominance Using Target-Based Features

Building on our previous findings, we developed a machine learning model to predict eye dominance directly from target-based features. The model uses only the target's horizontal and vertical visual angles from the user's head center to assess how well spatial position alone accounts for the dominant eye.

7.1.1 Classifier Training

All models were implemented in scikit-learn (v1.4.2), and hyperparameters were set to their defaults unless otherwise specified: logistic regression employed L2 regularization, SVM utilized an RBF kernel with C = 1.0, random forest used 500 trees with a maximum depth of 3, and gradient boosting employed 500 estimators with a learning rate of 0.1. A balanced class weighting was applied, except in GBC, as it does not support a class weight parameter. We did not perform additional hyperparameter tuning to avoid overfitting on the relatively small dataset.

We compared the performance of four different models: logistic regression, support vector machines (SVM), gradient boosted classifier (GBC), and random forest, using only horizontal and vertical target positions. Each trial was labeled by the dominant eye (1 = right-eye dominance, 0 = left-eye dominance).

All features were scaled using StandardScaler to ensure stable training. StandardScaler transforms a feature by centering it at zero and scaling it to unit variance, so that the resulting values have a mean of 0 and a standard deviation of 1, using the formula $X_{\text{scaled}} = \frac{X-\mu}{\sigma}$.

7.1.2 Model Evaluation

We evaluated the models using a leave-one-subject-out (LOSO) scheme, which provides the most stringent test of generalization by training on all participants except one and assessing on the individual left out. Table 7.1 presents the classification report of the four tested models using only target-based features. The highest accuracy was achieved using the GBC (0.724 ± 0.340), which also presented the highest weighted precision (0.733), weighted recall (0.727), and weighted F1-score (0.637). The logistic regression yielded the highest ROC AUC (0.818), macro recall (0.564), and macro F1-score (0.537).

7.2 Classifying Eye Dominance With Target and User-Based Features

Models based solely on target location achieved only modest performance, suggesting that spatial features alone are insufficient for reliable classification. We therefore investigate whether eye dominance predictions based on target-based features (horizontal and vertical angle), individual-level characteristics (IPD, visual acuity, corrected vision, handedness), and 6DOF location and orientation (head, cursor) can yield a more robust and generalizable classification.

Table 7.1: Comparison of LOSO classification metrics across four models using only target-based features. GBC yields the most predictive performance while failing to detect eye dominance reliably. All models show weak detection of left eye dominance, reflecting the class imbalance.

Group	Metric	GBC	Logistic Regression	SVM	Random Forest
Overall	Accuracy	**0.724**	0.564	0.551	0.581
	ROC AUC	0.800	**0.818**	0.801	0.795
Per-class (0 = Left-eye)	Precision (0)	**0.748**	0.343	0.338	0.336
	Recall (0)	0.076	0.562	**0.588**	0.468
	F1-score (0)	**0.138**	0.426	**0.429**	0.391
	Support (0)	1600	1600	1600	1600
Per-class (1 = Right-eye)	Precision (1)	**0.726**	0.762	**0.763**	0.745
	Recall (1)	**0.990**	0.565	0.535	0.627
	F1-score (1)	**0.838**	0.648	0.629	0.681
	Support (1)	3962	3962	3962	3962
Averages	Macro Precision	**0.737**	0.552	0.550	0.540
	Macro Recall	0.533	**0.564**	0.561	0.547
	Macro F1-score	**0.488**	**0.537**	0.529	0.536
	Weighted Precision	**0.733**	0.641	0.640	0.627
	Weighted Recall	**0.727**	0.564	0.550	0.581
	Weighted F1-score	**0.637**	0.585	0.571	0.598

Notes. LOSO = leave-one-subject-out.

7.2.1 Feature Selection and Classifier Training

To evaluate performance, we selected and compared four widely used classification algorithms that cover both linear and non-linear approaches: Logistic regression, support vector machines, random forests, and the gradient boosting classifier. This selection provides a balanced view of predictive performance across different model families. These models followed an identical implementation and hyperparameter setting as in the previous section (cf. Section 7.1).

The initial input of our model was a 29-dimensional feature vector (horizontal target angle, vertical target angle, target x-position, target y-position, target z-position, left eye x-position, left eye y-position, left eye z-position, right eye x-position, right eye y-position, right eye z-position, cyclopean eye x-position, cyclopean eye y-position, cyclopean eye z-position, handedness (Cat.), cursor x-position, cursor y-position, cursor z-position, IPD, LogMAR left eye, LogMAR right eye, LogMAR difference between eyes, corrected vision (Cat.), head x-position, head y-position, head z-position, head pitch, head yaw, head roll). To identify the most predictive yet non-redundant features, we implemented a multi-stage preprocessing and feature selection pipeline and applied it to each classifier. All pre-processing and feature selection steps (scaling, correlation filtering, L1 regularization, and RFECV) were performed strictly within each training fold of the cross-validation procedure to avoid data leakage from the test set. We evaluated different scaling methods (standard, min–max, quantile, and robust) in conjunction with logistic regression to ensure

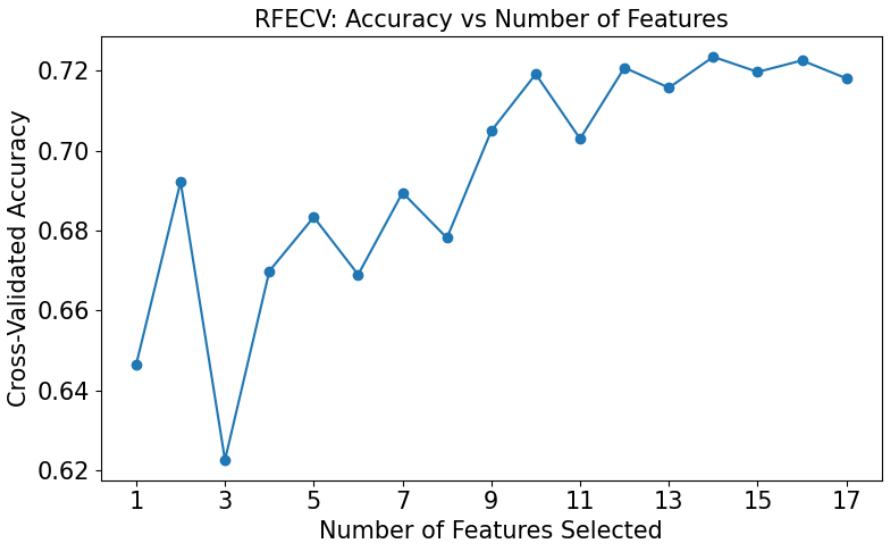


Figure 7.1: RFECV selected features vs. accuracy.

feature magnitudes contributed comparably to the models. For each scaler, the data were normalized, classifiers were trained, and performance was evaluated on the test fold using 5-fold cross-validation. We selected the Robust Scaler $X = \frac{X - X_{median}}{IQR}$ for normalization, as it achieved the highest accuracy (ROC AUC = 0.731) on the testing fold.

A correlation filter removed any pair of features with a Pearson's correlation coefficient $r > 0.8$ to reduce redundancy (cf. Figure A.1, A), (target x-position, right eye x-position, right eye y-position, right eye z-position, cyclopean eye x-position, cyclopean eye y-position, cyclopean eye z-position, cursor y-position, head x-position, head y-position, head z-position). L1-regularized models (Lasso with an L1 penalty) further refined the feature space by driving irrelevant coefficients to zero (head roll, target z-position, dominant hand). Finally, a recursive feature elimination with cross-validation (RFECV) iteratively evaluated feature subsets and optimized the balance between model complexity and predictive performance (cf. Figure 7.1).

This resulted in a set of 14 final features: horizontal target angle, target y-position, left eye positions (-x, -y, -z), LogMAR of the left eye, LogMAR of the right eye, LogMAR difference of both eyes, inter-pupillary distance (IPD), corrected vision, cursor x-position, cursor z-position, head pitch, and head yaw. Figure Figure 7.2 presents the feature importance of the L1 logistic regression.

We tested four models: logistic regression, random forest, SVM, and gradient boosting classifier. We applied RobustScaler in the feature selection pipeline, yet re-evaluated different models and scalers after final selection. For GBC, StandardScaler performed slightly better, consistent with GBC's lower sensitivity to scaling, and to ensure comparability, all models were scaled with StandardScaler.

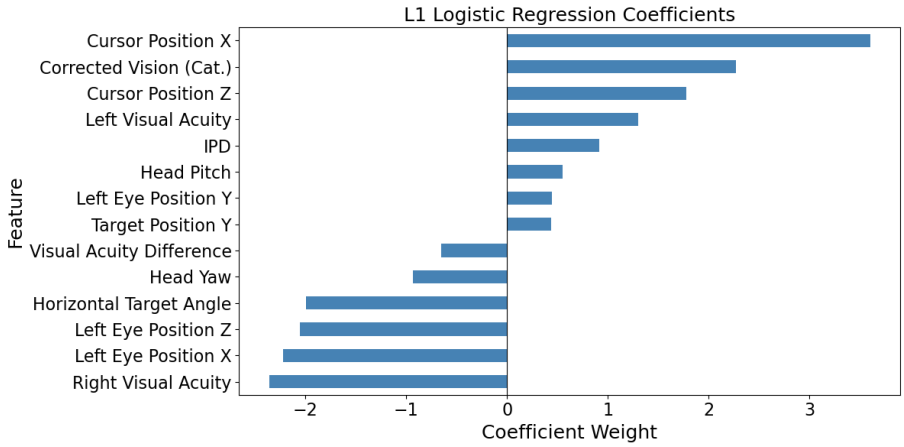


Figure 7.2: L1 logistic regression importance of final features. Three features were excluded.

We trained the GBC using the 14 features: horizontal target angle, target y-position, left eye x-position, left eye y-position, left eye z-position, LogMAR of the right eye, LogMAR of the left eye, LogMAR difference of both eyes, interpupillary distance (IPD), corrected vision (Categorical), cursor x-position, cursor z-position, head pitch, and head roll. Each trial was labeled by the dominant eye (1 = right-eye dominance, 0 = left-eye dominance). The model used 500 estimators, a maximum depth of 3 per tree, a learning rate of 0.1, with random state fixed at 42 for reproducibility. No class weighting was applied to GBC, which lacks this parameter; the other models used balanced class weights.

7.2.2 Model Evaluation

Model performance was evaluated using a leave-one-subject-out (LOSO) cross-validation, identical to the target-only feature model in the previous section (cf. Section 7.1). Table 7.2 displays the classification metrics of all trained models using target-based and individual features. Across the 28 participants, the GBC achieved the highest average accuracy of 0.778 (SD = 0.235) across all models. It also yielded the best macro F1-Score (0.721) and weighted F1-Score (0.775). The ROC AUC of 0.818 indicates that the model substantially outperformed chance (0.5) in discriminating between left- and right-eye dominance. Logistic regression achieved a slightly higher ROC AUC of 0.861.

7.3 Discussion

In this work, we developed and compared predictive models using ecologically valid variables, readily available in real life, to detect eye dominance in real time. Results demonstrate that the target position, crucially with a vertical viewing angle, provides

Table 7.2: Comparison of LOSO classification metrics across four models using target- and individual-based features. GBC demonstrated overall highest performance metrics. Logistic regression and SVM are also considered acceptable alternatives.

Group	Metric	GBC	Logistic Regression	SVM	Random Forest
Overall	Accuracy	**0.778**	0.711	0.723	0.707
	ROC AUC	0.818	**0.861**	0.857	0.790
Per-class (0 = Left-eye)	Precision (0)	**0.630**	0.503	0.5204	0.488
	Recall (0)	0.561	**0.608**	0.607	0.184
	F1-score (0)	**0.594**	0.550	0.560	0.268
	Support (0)	1600	1600	1600	1600
Per-class (1 = Right-eye)	Precision (1)	**0.830**	0.827	**0.830**	0.737
	Recall (1)	**0.867**	0.757	0.774	0.922
	F1-score (1)	**0.848**	0.791	0.801	0.819
	Support (1)	3962	3962	3962	3962
Averages	Macro Precision	**0.730**	0.665	0.675	0.613
	Macro Recall	**0.714**	0.682	0.690	0.553
	Macro F1-score	**0.721**	0.670	0.681	0.543
	Weighted Precision	**0.773**	0.734	0.741	0.665
	Weighted Recall	**0.779**	0.714	0.726	0.710
	Weighted F1-score	**0.775**	0.721	0.732	0.660

Notes. LOSO = leave-one-subject-out.

limited predictive power. The addition of individual-based features (e.g., head and cursor movement, visual acuity, eye position, IPD, and corrected vision) improves predictive performance, particularly in the detection of the minority class. Thus, our findings indicate that participant-specific patterns are central for real-time eye-dominance.

7.3.1 Target-Based Prediction

When predicting eye dominance solely based on target features, GBC presents the highest accuracy and weighted F1 overall. Yet, low macro F1-scores reflect the pronounced class imbalance, consistent with prior findings of a 70/30 right–left eye dominance distribution [107]. However, GBC performs unevenly, nearly failing to detect left-eye dominance (recall ≈ 0). ROC AUC values show reasonably strong discrimination above chance (0.5). GBC achieved the best macro scores but likely failed due to dataset imbalance.

Logistic regression showed the best discrimination (ROC AUC) and balanced accuracy (macro recall, F1), but all models struggled to detect left-eye dominance, suggesting target location features alone are insufficient

7.3.2 Target and Participant-Based Prediction

Combining target-based with additional participant-based features presented more stable predictive models. All models show somewhat equal scores, yet there is a slight favoring towards GBC. GBC yielded overall the highest accuracy, macro precision, macro recall, macro F1, weighted precision, weighted recall, and weighted F1, while maintaining good and consistent performance across classes. Furthermore, the ROC AUC is good; however, a logistic regression model showed a slightly higher value.

Compared to the target-based models, when including participant-based features, all models perform consistently better. Moreover, left eye cases are detected at much higher recall scores. Adding the user-specific features creates more informative signals to models for more accurate classifications, regarding both accuracy and class balance.

These results underscore the need for additional, readily available, and measurable user-level features to facilitate the accurate detection of eye dominance. GBC appears to be the most effective overall, while logistic regression and SVM provide reliable alternatives, with higher sensitivity towards detecting left-eye dominance.

7.3.3 Predictive Features

The features included in our models mostly align with findings of previous work. As we showed earlier in Chapter 6 (Section 6.2.2), vertical target angle has a subtle effect on eye dominance. The target Y-position captures this effect. The inclusion of horizontal target angle reflects our previous results, highlighting its role in eye dominance.

Including head pitch and yaw captures head-tilt behavior related to eye dominance [39]. Similarly, the eye position (XYZ)-feature may also capture this, as eye position changes with head orientation. Using visual acuity of both eyes, including their difference, as predictive features confirms the relationship between ocular dominance and visual acuity [75]. Furthermore, the categorical feature of corrected vision shows that, irrespective of correction status, differences in visual acuity still contribute to eye dominance behavior. Cursor X-positions as a predictive feature translates to hand alignment across the horizontal axis, consistent with results showing the alignment of a finger or cursor with the dominant eye [105, 61, 26]. IPD and target Z-positions were included, yet their individual contributions remain unclear. Further detailed analyses could clarify their roles in eye dominance.

7.3.4 Implications and Challenges

Our real-time predictive model enables systems to adapt to users' eye dominance, improving selection accuracy. Previous studies reported an average systematic displacement exceeding 42.46 cm when pointing from distances of 2 and 3 meters, without accounting for eye dominance [81, 83]. Alignment-based techniques would

equally benefit from knowledge about dynamic eye dominance. For instance, HeadCrusher [104] or Gaze&Finger [78, 147] could benefit from eye dominance prediction, reducing a selection offset.

In cursor-free applications like VR films or simple label placement ([32]), the dominance prediction algorithm could align content to the user's visual vantage point. Models relying solely on user-based features would be applicable in scenarios where target locations are unknown. Further feature engineering and validation of alternative feature sets could improve performance, ensure reliability, and generalizability in real-world scenarios.

7.3.5 Limitations

We address several limitations that inform future work. First, our HMD-anchored targets may limit transferability to world-fixed scenarios, although prior work suggests depth does not influence eye dominance variability. Second, dataset imbalance may have constrained model performance; a larger, richer dataset would improve predictions, and we open-source our data to support future research. Finally, the scope of our findings is restricted because our evaluation is based only on a subset of classifiers. The inclusion of neural networks and other advanced models may capture feature-class relationships in more depth.

7.4 Chapter Summary

In this chapter, we trained and compared predictive models to detect eye dominance based on user-specific and target-based features. These features are ecologically valid variables, readily available in real life. The results indicate that predicting eye dominance benefits significantly from incorporating user-specific features, while target-based features alone are insufficient for robust prediction. Thus, our findings indicate that participant-specific patterns are central for real-time eye dominance prediction. Gradient boosted classifiers emerged as the most effective approach, with logistic regression and support vector machine also providing reliable detection, including the less frequent left-eye dominance. These findings have practical implications for adaptive XR interactions, where understanding individual eye dominance and its dynamic patterns can enhance selection accuracy and overall user experience.

Chapter 8

Discussion

The previous chapters of this thesis have explored eye dominance, its dynamics, and its potential application to 3D immersive environments. By understanding how eye dominance behaves and changes, how it can be determined reliably in 3D contexts, and its potential applications in HCI, we can provide insights into best practices. In the following chapter, we reflect on our results in the context of our leading research questions presented in Chapter 1. We then outline the practical implications and present guidelines for examining, considering, and leveraging eye dominance effectively. We outline three core application ideas of leveraging eye dominance, including image-plane pointing, foveated rendering, and visual layouts. Finally, we discuss the limitations of this work and suggest future research avenues that build upon these insights, including which additional foundational aspects to explore and how eye dominance can be leveraged or inform HCI design.

8.1 Research Questions

Understanding eye dominance, each eye's individual contribution, and how it changes enables the design of more precise and naturalistic 3D interactions. With our leading research questions, we provide a starting point for implementing and uncovering eye dominance in HCI, supporting more informed, user-sensitive interaction design.

8.1.1 RQ 1: What is eye dominance, and what potentials for application in human-computer interaction does it offer?

Eye dominance has been a long-standing topic in vision science, yet it remains a loosely understood and debated concept in HCI. Exploring the implications of eye dominance for HCI begins by establishing a theoretical foundation, which motivates

our first research question. In a systematic literature review Chapter 2, definitions, testing methods, and behavioral features related to eye dominance are synthesized to foster a thorough understanding.

Eye dominance refers to an asymmetric visual processing that occurs during tasks like pointing and alignment, affecting hand-eye coordination and revealing differences in perceptual behavior between the eyes. Additionally, the dominant eye shows several behavioral and perceptual differences. For example, a user's pointing and alignment are biased, and objects are perceived as larger and sharper with the dominant eye. Contrary to previous assumptions, the dominant eye exhibits a dynamic behavior, changing in response to contextual and individual factors. Despite the strong interest in expert fields, there is no standard testing procedure, hindering reproducibility for HCI studies and leading to inconsistent results across methods.

Some HCI work has shown interest in eye dominance either via implementation or testing within a study, yet these numbers are scarce. Furthermore, eye dominance is framed in a limited way. In addition to neglecting the variety of perceptual differences and advantages the dominant eye holds, the dynamics arising from contextual and individual factors remain unacknowledged in HCI.

The application potential of eye dominance in HCI is diverse. The current literature on eye dominance in HCI has demonstrated promising applications in 3D user interfaces, content presentation, cursor placement, energy optimization, and display viewing evaluation. Given the perceptual advantages and key relevance to pointing and alignment behavior, interaction techniques or content presentation in reference to the dominant eye hold high potential for increased accuracy and user experience. Asymmetric foveated rendering based on the dominant eye has exhibited significant energy savings while remaining unnoticed by users.

8.1.2 RQ 2: How does eye dominance behave during interaction in 3D environments?

In Chapters 3, 5 and 7, we explored the behavior and influential factors of eye dominance experimentally within 3D environments. To enable the investigation of eye dominance and its dynamics, we designed and compared classification procedures.

8.1.2.1 RQ 2a: How can eye dominance be objectively measured and characterized in 3D environments?

As seen in Chapter 2, vision science primarily emphasizes the task dependency of eye dominance. Hence, testing for eye dominance should essentially mimic the environment in which it is leveraged. For this reason, we developed and evaluated eye-dominance testing procedures designed specifically for VR contexts.

During simple VR alignment tasks, we compared distances between the target, cursor, and eye. This allowed us to determine with which eye a participant aligned a virtual cursor and thereby identify the dominant eye. Our results showed strong alignment of our in-HMD test with two traditional tests (Miles test, Hole-in-card test). With this method, we provide a valid alternative for traditional, real-life tests, for applications of eye dominance within AR and VR settings.

8.1.2.2 RQ 2b: Which factors influence eye dominance and how does it change in 3D interaction?

While the vision science literature demonstrates a correlation between eye dominance and stable characteristics (hand preference and heritability), a range of other factors influence which eye dominates within an individual. We demonstrated dynamic behavior in 3D, contradicting the previous assumption of static, fixed eye dominance.

Our results show that factors influencing eye dominance can be distinguished into two categories: *individual and contextual factors*. Individual factors refer to user-centric traits that shape the eye dominance behavior. For instance, the hand used during hand-eye coordinated motor movement has been shown to influence eye dominance, as confirmed in our studies. Contextual factors, in turn, are external conditions or situational circumstances that can determine which eye is dominant and induce a reversal. These include elements in the task, interaction context, or viewing conditions. From our work, we confirmed that the horizontal viewing angle influences eye dominance, also in VR settings, aligning with previous work [58]. The vertical axis amplifies this effect: lower vertical levels, the vertical bias increases, and vice versa. As a result, eye dominance switches are more likely to occur at lower angles. However, we also observed a less pronounced effect of eye dominance reversals than previously assumed ([58]) and observed in our first study (Chapter 3). Moreover, we observed high variability among participants, suggesting that it is a nuanced trait inherent to individuals.

Overall, right-eye dominance is most prevalent in our results, consistent with reports from previous literature. Yet individuals may also exhibit inconsistencies in their own eye dominance patterns. This highlights the nuanced nature of eye dominance. Relying on a static, or even generic model of eye dominance is insufficient, emphasizing the need for user-adaptive mechanisms.

8.1.3 RQ 3: Can we predict eye dominance in 3D interaction?

In Chapter 7, we explored the automatic inference of eye dominance using an ML model. The results show that features most predictive of automatic eye dominance detection are a combination of both context- and user-specific variables. We achieved only modest predictive performance when using the target location (horizontal and

vertical viewing angle) as the only features. When including the individual features, predictive performance improved. Our final model consists of both user-centric and context-specific features: *head and cursor movement, visual acuity, eye position, inter-pupillary distance (IPD), horizontal and vertical viewing angle.* This highlights the importance of integrating multiple sources to predict a user's eye dominance accurately for 3D interaction.

8.2 Lessons Learned and Future Implications

Whether incorporated as a design factor or as a recorded demographic variable, the inclusion of eye dominance would ensure the development of adaptive, user-centered technologies and the exploration of functional differences between and within users. Based on the results of the previous chapters and our leading questions, we discuss the implications for leveraging eye dominance effectively in 3D environments on theoretical, methodological, and practical grounds.

8.2.1 Do not assume static eye dominance

Based on our previous chapters, we clearly highlight the dynamic nature of eye dominance. When implementing eye dominance in HCI, both individual factors (head and cursor movement, visual acuity, eye position, IPD) and contextual factors (task elements, interaction context, or viewing conditions) can influence which eye dominates. A theoretical implication is avoiding the reliance on simplistic, universal models of eye dominance behavior. Instead, we recommend assessing relevant factors that induce changes in eye dominance, both context-dependent factors and individual differences between users.

8.2.2 Define, measure, and report eye dominance: it could be a covariate

When working with gaze-based interfaces or interactions, we suggest routine testing for and reporting of eye dominance. As we have explored the behavioral differences associated with eye dominance, it should be considered a covariate in studies. It influences pointing behavior, depth perception, cursor movements, or explains unexpected variance. Thus, we recommend specifying eye dominance and measurement using a standardized and precise testing procedure, as outcomes vary across tasks and testing methods. This methodological implication of precise reporting of test outcomes is particularly relevant for HCI studies, facilitating easier interpretation, comparison, and replication.

8.2.3 Use multiple eye dominance tests for real-life contexts

The literature from both vision science and psychology has shown the absence of a standard testing and reporting procedure. The multiple procedures available produce inconsistent results. This enhances the need for an eye dominance testing and reporting protocol. Hence, to ensure accurate results in controlled experiments, we recommend using multiple eye dominance tests rather than relying on a single method, which may yield incorrect or inconsistent outcomes. Combining tests and determining a majority consensus provides a more stable classification while reducing the likelihood of ambiguous results. Utilizing various methods, such as the hole-in-card, Miles, and in-HMD VR tests, ensures a comprehensive evaluation and minimizes instances where no definitive value can be determined. Our automatic in-HMD testing method offers significant advantages for applications and calibration procedures, specifically for VR environments. It further eliminates the need for participants to close an eye or verbally indicate their observations, as the system automatically tracks and determines eye dominance.

8.2.4 Standardize eye dominance testing protocols

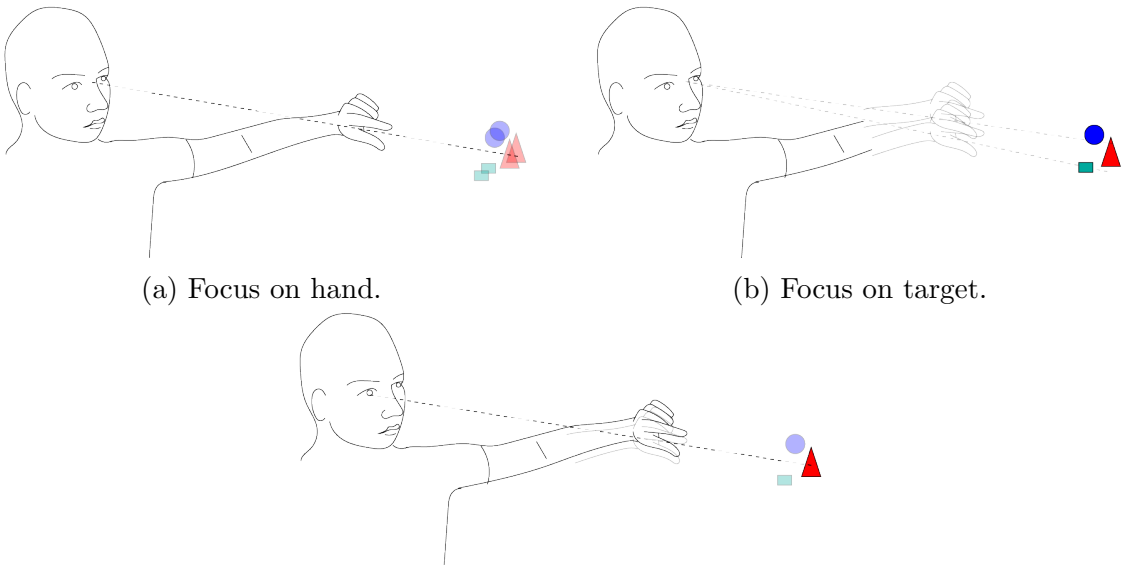
Eye dominance test protocols should be conducted with clear and standardized instructions to ensure consistency and prevent ambiguity or misinterpretation. It is crucial to emphasize that participants must avoid any additional hand movements or postural adjustments when pointing, as these can introduce variability in the results. When conducting tests, it is ideal to use participants who are naïve to the testing purpose to minimize the risk of subconscious pre-selection of their dominant eye. Additionally, eye dominance is best assessed in the same environment where it will be applied, as contextual factors may influence the results. Furthermore, transparent reporting of testing parameters (target/testing distance, hand usage, procedures) will facilitate easier replication and contextualization of outcomes.

8.3 Opportunities for HCI

Given the increasing use of immersive environments and interactive technologies, understanding and integrating eye dominance benefits the accuracy and efficiency of interactive systems, presenting an opportunity for HCI. This section provides concrete practical examples that could benefit from incorporating eye dominance into user interfaces or merely considering it as a confounding variable in visual perception and interaction studies.

8.3.1 Image-plane Pointing

Many spatial interaction tasks, such as pointing, selecting, or aligning objects in 3D space, rely on accurate eye-hand coordination. Eye dominance can influence performance by biasing spatial perception, for example, how a user judges the



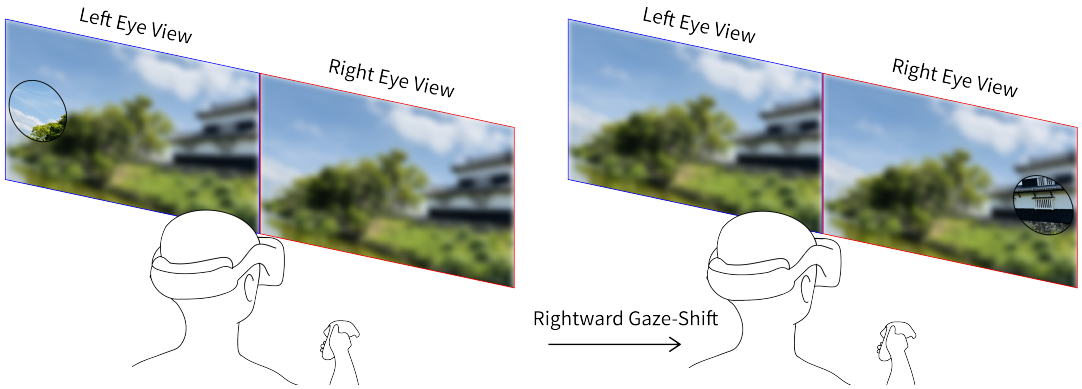
(a) Focus on hand.

(b) Focus on target.

(c) Targeting supported by eye dominance.

Figure 8.1: Conceptual illustration on how eye dominance can support targeting during image-plane pointing. (a) and (b) assume the cyclopean eye as the reference point. Due to misalignment, selection requires adjustment, leading to difficult selection of the red triangle. (c) uses the dominant eye as the reference point, making selection easier by immediately relying on the user's "natural" line-of-sight formed by the dominant eye, the hand, and the target. The benefit arises during targeting.

position or alignment of objects relative to themselves. Specifically, vision science findings suggest that the dominant eye serves as a reference point for spatial judgments and actions (see Section 2.3.4.1). Interactive systems, however, are unaware of this and fail to account for eye dominance, leading to inaccuracies and difficulties in 3D selection, such as image-plane pointing. In image-plane pointing, users align a hand-held pointer or their finger with the target. One key issue arises during selecting distant targets: the further the target, the more noticeable the parallax error. Because of that, double vision occurs at either the hand (Figure 8.1a), the target (Figure 8.1b), or the cursor (Figure 8.1c). This becomes especially problematic in visually dense or cluttered environments, where precise target selection is essential but also difficult. As the dominant eye drives image-plane pointing, the user's initial movement aligns the target with the dominant eye. If the system does not leverage knowledge about the dominant eye, the user has to adjust and correct the alignment so that it works with the system, which might use the cyclopean eye. A key factor contributing to these challenges is that humans naturally use their dominant eye when pointing [105, 80]. One possible solution is to calibrate the interactive system to the user's dominant eye and compute pointing vectors accordingly. By modeling the pointing vector as emerging from the dominant



(a) Right-eye dominance (b) Left-eye dominance

Figure 8.2: Conceptual illustration of dynamic foveated rendering leveraging eye dominance. (a) The left-eye view is rendered at a higher resolution in the foveal (central) region. After a rightward gaze shift, (b) the system adapts by rendering the right-eye view aligned with the right dominant eye at higher resolution.

eye and passing through the finger position, the system can better estimate the intended target, increasing accuracy and improving user interaction, as successfully demonstrated in previous work with central static targets [90]. Extending this approach to dynamic targets and adaptive eye dominance detection could further improve interaction. Similarly, incorporating eye dominance might improve other interaction techniques, such as 3D pointing, grasping, cursor selection, or gesture input, thereby enhancing accuracy and minimizing selection errors.

8.3.2 Foveated Rendering

Perception-driven rendering leverages the human perception system to increase the quality and efficiency of visual output. Foveated rendering, one perceptual rendering technique, optimizes computation by delivering high-resolution content only within the user's foveal (central) region. Content in the non-foveal region (e.g., periphery) is rendered with lower quality [152]. This is — if done correctly — unnoticeable by the user. Therefore, detailed rendering is confined to what the user can perceive with high acuity, reducing the amount of work the graphics processing unit has to do. Previous work has explored incorporating static eye dominance into foveated rendering to enhance visual performance and resource efficiency [86]. However, this thesis has demonstrated that eye dominance exhibits a more dynamic or fluctuating nature, shaped by both individual and contextual factors. This approach can be extended by leveraging the perceptual asymmetries and dynamic nature of eye dominance, potentially achieving greater computational savings while preserving visual fidelity for the user. For example, accounting for the dynamic behavior of eye dominance in response to horizontal gaze shifts could avoid perceptual inconsistencies in foveated rendering, especially during rapid changes

in fixation points across the visual field. However, empirical validation is needed to ensure that dynamically adapting rendering based on eye dominance does not introduce new perceptual inconsistencies or discomfort.

The dynamic nature of eye dominance may have implications for eye-dominance-guided foveated rendering. On the one hand, treating it as static when it is not might lead users to notice the low quality of the predetermined non-dominant eye after a switch. However, being overly sensitive to switches might also lead to repeated quality switches between the left and right eye, irritating users.

The elegance of foveated rendering is that it is not noticeable to users. Integrating eye dominance might disrupt this. Users might notice the lower quality when the algorithm considers an eye as dominant while it is not the dominant eye (and vice versa). One way to prevent this is to keep the compression level so low that it cannot be detected by the dominant eye. However, this would decrease the efficiency of foveated rendering. Another way is to have transition areas. For example, a prediction algorithm could offer a confidence score. If the confidence is too low, both eyes could see images from regular foveated rendering algorithms. Similarly, a calibration procedure or simple heuristics could define transition areas where the calibration or heuristics cannot accurately determine a dominant eye. With that, foveated rendering algorithms could rely on eye dominance in certain areas, increasing performance. In contrast, regular foveated rendering takes over in areas where the dominant eye is unknown or ambiguous.

8.3.3 Visual Layouts

Visual layouts, especially in complex or multi-display setups and highly dense and cluttered environments, can benefit from being optimized with the dominant eye in mind. Given the faster visual processing and superior performance of the dominant eye in visual search tasks [131], placing content within the dominant eye's field may enhance recognition speed, reduce cognitive load, and increase user experience. For example, aligning the labels with a user's dominant eye could improve precision and speed in 3D environments. Using the cyclopean eye (or the head-forward vector) as a reference point for view management and label placement and orientation might lead to suboptimal visualizations and occluded labels. Similarly, using the non-dominant eye can lead to misalignment of label and content, due to parallax (e.g. Figure 8.3a). Instead, developers can leverage the dominant eye to optimize orientation and position, as shown in work by [32] or illustrated in Figure 8.3b. Both personalizing visual layouts based on prior eye dominance calibration and based on real-time detection could enhance efficiency during high-focus tasks by subtly shifting content towards the user's dominant eye.

(a) (b)

Figure 8.3: Conceptual Illustration Dominant Eye Aware AR Visual Layout. a) Label placement in the non-dominant eye (left eye). Content and label are misaligned. b) Label placement in accordance with the users' dominant eye (right eye). Label is aligned with content.

8.4 Open Questions and Future Directions

While this thesis presents the feasibility of leveraging eye dominance for HCI, several limitations must be acknowledged. In the context of our research, we have explored eye dominance only within VR systems. Given the high susceptibility of eye dominance to task setup and context, environments such as augmented reality (AR) or 2D displays warrant additional exploration. While VR HMDs provide only a limited field of view, other contexts may offer a different viewing range. Nevertheless, this thesis lays the basis for future work with eye dominance. Hence, in this section, we propose some areas and unanswered questions for future exploration.

8.4.1 Online Detection

A central challenge for HCI when relying on eye dominance is accurately predicting which eye is dominant at any given time during the interaction. This thesis has shown that eye dominance depends on individual and contextual factors (Chapter 2, Section 2.3.3). Thus, developing automated, real-time methods for detecting eye dominance is necessary to leverage eye dominance in HCI fully. While we have taken a first step toward developing an ML model for eye dominance prediction, it requires further evaluation and application. A reliable, real-time detection system would enable scalable, objective assessment across interactive contexts.

One way to extend this work is to analyze differences in horizontal saccade velocity between the eyes. As outlined earlier (cf.Chapter 2, Section 2.3.4), the dominant eye typically exhibits faster horizontal saccades at reading distance. This behavior could be leveraged to infer the current dominant eye. However, leveraging it for automated detection would potentially require high-speed eye-tracking technologies,

such as event-based cameras [51], which can capture eye movements with greater temporal precision and measure inter-eye differences in saccade velocity. Such a model could then be incorporated into the standard eye-tracking calibration process, during which participants fixate on targets that disappear and reappear in new locations. By measuring the independent velocities of each eye during these gaze shifts, eye dominance can be calibrated effortlessly, eliminating the need for additional procedures for the user. To avoid calibration constraints, additional metrics may be combined to detect eye dominance reliably. Depending on performance and implementation, the model could also make predictions throughout the interaction or only at certain stages (e.g., during menu interaction). Regardless of implementation, such a model would enable HCI systems to fully leverage eye dominance by dynamically adapting interfaces based on real-time predictions. To ensure robustness and generalizability, its development must be grounded in established findings from vision science.

8.4.2 Opportunity for Multi-Point Testing

A need for multi-point testing may arise from the dynamic nature of eye dominance. While many systems and tests perform a one-off calibration at 0°, it remains unclear how changes in eye dominance, influenced by factors such as horizontal viewing angles [58] or handedness [61], affect system performance. This raises the question of whether single-point testing is sufficient or if multi-point testing procedures are necessary to account for variations in dominance across different contexts and ensure reliable system behavior. Further investigations are required to determine whether dynamic recalibration can improve performance in scenarios where eye dominance shifts.

8.4.3 One-off Calibration

Given our findings, showing both individual and contextual factors influencing eye dominance, Leveraging this, a calibration procedure that determines at which angle the dominant eye switches for a user could serve as a valid basis for user-specific profiles, which may be implemented for the application examples mentioned previously (cf. Section 8.3). This calibration could be performed in addition to the regular eye-tracking calibration during setup. In addition, it could also include other factors not yet explored.

8.4.4 Other Factors Influencing Eye Dominance

In this thesis, several individual and contextual factors were explored to examine potential influences on eye dominance. Yet, further factors remain unexplored. A thorough understanding of eye dominance is necessary to fully integrate it into foveated rendering algorithms. Otherwise, realizing its potential for optimal performance enhancements is impossible. Here, research on other factors leading to

switches in eye dominance is necessary. Isolating factors in experimental laboratory studies (e.g., disparity, head and torso movements, target sizes) and testing which eye is dominant can provide further insights into eye dominance. These findings can then be translated and integrated into applications for interactive environments to improve usability and user experience.

8.4.5 Real-time Prediction

Dynamic eye-dominance-guided foveated rendering should, at best, adapt to changes in eye dominance by continuously detecting the users' current dominant eye. Here, a key challenge in developing a dynamic foveated rendering model is detecting the shift from one eye to another. While we have made a first step with the development of our predictive ML model using user-based and contextual features, the best classifier achieved an accuracy of 0.778. However, given that the literature reports a 70-30 split in right- and left-eye prevalence, a model with higher predictive performance is needed to detect the dominant eye reliably. Given our results, a new model should respect both individual and contextual factors. Further features should be explored to improve prediction. For example, by exploring differences in movements between the two eyes, such an algorithm might be derived, providing input for dynamic eye-dominance-guided foveated rendering.

8.4.6 Head, Neck and Body Movements

More foundational research on the interactions among head, neck, and body movements and eye dominance is required. To maintain exact target locations and thereby eye-in-head angles, the targets in each study were presented in positions relative to the HMD. Hence, whenever a participant rotated their head left or right, the target location remained at the specified eye-in-head angle. However, as eye, head, and body movements are coupled [133], the effects of this on eye dominance remain unknown. Given that these HMD-relative target locations are rare in XR contexts, this limitation should be addressed in future work to enable more ecologically valid scenarios. Furthermore, one previous study found a relation of a head-tilt (head-roll) to the left or right with the dominant eye [38]. Hence, a future research area is to explore whether a head tilt or rotation takes place in response to eye dominance. Including additional postural data, such as head, neck, and torso, would yield more ecologically valid results.

8.4.7 Context-Dependency and Dynamics

Tools like augmented and virtual reality enable the presentation of dynamic and wide-ranging stimuli, varied depths, and task-dependent visual alignments that more closely mimic real-world conditions while still offering a high level of control over the stimuli. While traditional non-immersive environments can isolate physiological factors influencing eye dominance, such as static targets, they may not reflect the

complex interactions during more naturalistic tasks. Especially in light of the inconsistent findings discussed earlier (cf. Section 2.3.3.2), such as those related to viewing distance, advancements in AR/VR could enable more precise control of variables, thereby improving the investigation of potential effects and influences in vision science. We provided a first step toward investigating eye dominance by presenting dynamic VR stimuli that elicit various gaze behaviors. However, it remains unknown whether the technology itself — such as an HMD, an optical see-through display, or a display wall —influences eye dominance, underscoring the need for careful consideration and evaluation. Thus, using AR/VR to explore eye dominance and the influence of AR/VR hardware on it are intertwined challenges. This points towards a need for factorial experiments. For example, the replication of real-world experiments in AR and VR and using the unique capabilities of AR/VR to isolate factors such as viewing distance and viewing angles. Together, this would help clarify the dynamics and context-dependency of eye dominance.

Chapter 9

Conclusion

This thesis explored the foundational behavior of eye dominance, how it changes, and discussed how it may be leveraged in 3D environments. The results display the variability of eye dominance, challenging the common assumption that it is a static trait. We investigated how it shapes perception and interaction in 3D immersive environments and explored objective measurement techniques tailored to these environments. Acknowledging which eye is dominant and how it changes can help create more accurate interactions, optimize energy consumption, and increase overall user experience. Although eye dominance has been addressed in some HCI work, it is typically framed as unchanging, which limits its applicability and biases subsequent research and design choices. By integrating theoretical and empirical methods, this work demonstrated that eye dominance can vary in response to various factors and that it warrants consideration in HCI.

We highlight that eye dominance is not fixed, but dynamic and nuanced. It introduces an asymmetry in visual processing, thereby affecting both perception and interaction. Both context-dependent and user-centric factors can influence which eye is dominant. The hand used for alignment, the visual acuity of each eye, and the horizontal and vertical viewing angles have led to a change in eye dominance. However, the response to each of these factors remains unique to the individual. For instance, although the viewing angle induces a change in eye dominance, the exact angle at which this occurs varies from person to person. Nevertheless, the synergy between these factors yields more reliable and robust estimates of a user's eye dominance behavior than relying solely on contextual cues.

By revealing how eye dominance behaves and is influenced, this work highlights opportunities for immersive systems. While some existing HCI work has implemented or tested eye dominance, its dynamic nature is not acknowledged. If the dynamic behavior and influencing factors are recognized, it may serve as a paradigm for how interactive systems can respond systematically. In VR and AR, by adapting visual experiences in real time, usability, accuracy, and interaction quality may be

enhanced. For instance, aligning virtual objects with the dominant eye rather than the cyclopean eye may offer more intuitive depth perception. Integrating a dynamic eye dominance model into foveated rendering can improve adaptability, enhancing computational efficiency while remaining imperceptible to the user. Considering eye dominance as a potentially confounding variable within user studies may clarify how the visual asymmetry and individual differences influence performance or perception. Together, these findings highlight the need for acknowledging individual perceptual asymmetries when designing interactions for 3D immersive environments. We believe incorporating eye dominance will enhance interaction and user experience for extended reality (XR). By considering a user's unique eye dominance behavior, we can create more personalized and adaptive interfaces.

With this thesis, we highlight and strengthen the topic of eye dominance in HCI. Building on its perceptual advantages, we present concrete applications of eye dominance in image-plane pointing, foveated rendering, and visual layouts. Furthermore, we outline practical implications for HCI researchers and designers, highlighting best practices for testing eye dominance, implementation, and consideration in future work. Lastly, we provide calibration and prediction methods for eye dominance. We introduce a VR-specific eye dominance testing method, designed for immersive environments. Our machine learning model predicts eye dominance based on user-specific and context-specific factors, enabling real-time detection in immersive environments.

We suggest that future work should leverage or account for eye dominance in empirical studies, analytical models, and interaction design. While we have examined several factors contributing to eye dominance, future work should also consider task demands, visual environment, and additional user-specific factors that may influence which eye becomes dominant. Additionally, exploring other perceptual distinctions of the dominant eye may create additional opportunities for HCI design. In work involving perception or interaction, eye dominance should be treated as a potentially confounding variable.

As personalized, interactive systems become increasingly prevalent, adapting to individual visual behaviors becomes inevitable. Hence, re-conceptualizing eye dominance from a static behavior to a dynamic visual characteristic is not only practical but also highly necessary. By acknowledging variability, interactive systems can become more personalized and responsive to differences among users, ultimately enhancing the user experience.

Appendix A

Additional Materials

A.1 Task Demonstrations Digital Appendix

Video demonstration of study tasks available on: https://doi.org/10.5281/zenodo.18862982

A.2 Systematic Literature Review Additional Material

Table A.1: List of included articles

Title	DOI	Year	Authors	Category
Ocular dominance demonstrated by unconscious sighting	https://doi.org/10.1037/h0075694	1929	W. R. Miles.	Vision Science
Ocular dominance in human adults	http://dx.doi.org/10.1080/00221309.1930.9918218	1930	W. Miles	Vision Science
A note on an attempt at judging ocular dominance from photographs	https://doi.org/10.1037/h0071679	1930	Downey, JE	Vision Science
A simple test for ocular dominance	https://doi.org/10.2307/1414250	1931	Scheidemann, NV	Vision Science
The dependence of eye-hand coordinations upon eye dominance	https://doi.org/10.2307/1414538	1932	Lund FH	Vision Science

Title	DOI	Year	Authors	Category
The monoptometer: A new device for measuring eye-dominance	https://doi.org/10.2307/1414965	1932	Lund, FH	Vision Science
A comparison between the miles A-B-C method and retinal rivalry as tests of ocular dominance	https://doi.org/10.2307/1415504	1934	Washburn, MF; Faison, C; Scott, R	Vision Science
The Relative Importance of Eye and Hand Dominance in a Pursuit Skill	https://doi.org/10.2307/1416715	1935	G. L. Freeman and J. S. Chapman	Vision Science
Ocular dominance - Its independence of retinal events	https://doi.org/10.1001/archopht.1936.00840170102009	1936	Schoen, ZJ; Wallace, SR	Vision Science
Some relations of dominant eye and hand	https://doi.org/10.1111/j.1444-0938.1937.tb05780.x	1937	Towns F.G.H.	Vision Science
The dominant eye	https://doi.org/10.1111/j.1444-0938.1937.tb05779.x	1937	Fraser R. S.	Vision Science
A consideration of the use of the term ocular dominance	https://doi.org/10.1097/00006324-193811000-00003	1938	Clark B.; Warren N.	Vision Science
The dominant eye - Its clinical significance	https://doi.org/10.1001/archopht.1938.00850160081005	1938	Fink, WH	Vision Science
A suggested device for determining eye dominance objectively with scientific accuracy	https://doi.org/10.1037/h0057960	1940	Scheidemann, NV; Kandle, MW	Vision Science
An eye dominance gage and some of its uses	https://doi.org/10.1080/00221309.1942.10544723	1942	Diehl H.T.	Vision Science
A battery of tests for the dominant eye	http://dx.doi.org/10.1080/00221309.1944.10543187	1944	Crider BA.	Vision Science

Title	DOI	Year	Authors	Category
Ocular dominance, its measurement and significance	https://doi.org/10.1111/j.1444-0938.1945.tb00197.x	1945	LedererJ.	Vision Science
A theory of ocular dominance	https://doi.org/10.1001/archopht.1951.01700010395005	1951	Walls, GL	Vision Science
Relation of ocular dominance, handedness, and the controlling eye in binocular vision	https://doi.org/10.1001/archopht.1953.00920030613007	1953	Berner, GE; Berner, DE	Vision Science
Eye-dominance and head-tilt	https://doi.org/10.2307/1419131	1960	Greenberg, G.	Vision Science
A method for investigation of ocular dominance based on optokinetic nystagmus	https://doi.org/10.1111/j.1755-3768.1961.tb00246.x	1961	Enoksson P.	Vision Science
Ocular Dominance	https://doi.org/10.1111/j.1444-0938.1961.tb06505.x	1961	Lederer J.	Vision Science
Theories and Tests on Ocular Dominance	https://doi.org/10.1111/j.1444-0938.1961.tb02072.x	1961	Kuhn M.	Vision Science
A group-test for assessing hand- and eye-dominance	https://doi.org/10.2307/1419611	1962	Crovitz HF, Zener K.	Vision Science
Reaction time under three viewing conditions: Binocular, dominant eye and nondominant eye	https://doi.org/10.1037/h0039953	1964	Minucci PK, Connors MM.	Vision Science
Monocular and binocular perception of verticality and relationship of ocular dominance	https://doi.org/10.2307/1421303	1966	Schneider, CW	Vision Science
Braindedness, handedness and eyedness: The meaning of ocular dominance	https://doi.org/10.1111/j.1444-0938.1970.tb01054.x	1970	LedererJ.	Vision Science
Monocular-binocular coordination vs. hand-eye dominance as a factor in reading performance	https://doi.org/10.1097/00006324-197102000-00005	1971	Brod N, Hamilton D.	Vision Science

Title	DOI	Year	Authors	Category
Ocular Dominance: A test of two hypotheses	https://doi.org/10.1111/j.2044-8295.1971.tb02028.x	1971	D. M. A. Gronwall, H. Sampson	Vision Science
Studies on the functioning of sighting dominance	http://dx.doi.org/10.1080/14640747208400305	1972	J. Money,	Vision Science
Patterns of ocular dominance	https://doi.org/10.1097/00006324-197304000-00002	1973	Coren S.; Kaplan C.P.	Vision Science
Development of ocular dominance	https://doi.org/10.1037/h0036085	1974	Coren, S.	Vision Science
Effects of eye dominance and retinal distance on binocular rivalry	https://doi.org/10.2466/pms.1974.39.2.747	1974	Collins JF, Blackwell LK.	Vision Science
Is eye dominance a part of generalized laterality?	https://doi.org/10.2466/pms.1975.40.3.763	1975	Porac C, Coren S.	Vision Science
Relationship between eye dominance and monocular acuity - additional consideration	https://doi.org/10.1097/00006324-197612000-00007	1976	Porac, C; Whitford, FW; Coren, S	Vision Science
Size accentuation in the dominant eye	https://doi.org/10.1038/260527a0	1976	Coren S, Porac C.	Vision Science
Acuity and sighting dominance in children and adults	https://doi.org/10.1037/0012-1649.13.3.288	1977	Dziadosz, GM; Schaller, MJ	Vision Science
Assessment of motor control in sighting dominance using an illusion decrement procedure	https://doi.org/10.3758/BF03199484	1977	Porac, C; Coren, S	Vision Science
Sex differences in the relations among handedness, sighting dominance and eye acuity	https://doi.org/10.1016/0028-3932(77)90063-x	1977	Gur RE, Gur RC.	Vision Science
Sighting dominance and binocular-rivalry	https://doit.org/10.1097/00006324-197803000-00011	1978	Porac, C; Coren, S	Vision Science
Monocular asymmetries in recognition after an eye-movement - sighting dominance and dextrality	https://doi.org/10.3758/BF03206110	1979	Porac, C; Coren, S	Vision Science

Title	DOI	Year	Authors	Category
The variable angle-mirror, a new tool for the study of ocular dominance and eye fixation	https://doi.org/10.1111/j.1755-3768.1980.tb05710.x	1980	Björk A.	Vision Science
Sighting dominance: An explanation based on the processing of visual direction in tests of sighting dominance	https://doi.org/10.1016/0042-6989(81)90185-1	1981	Barbeito, R.	Vision Science
Monocular asymmetries in visual latency as a function of sighting dominance	https://doi.org/10.1097/00006324-198212000-00009	1982	Coren S, Porac C.	Vision Science
The cyclopean eye vs. the sighting-dominant eye as the center of visual direction	https://doi.org/10.3758/bf03206224	1982	Ono H, Barbeito R.	Vision Science
The relationship between sighting dominance and the fading of a stabilized retinal image	https://doi.org/10.3758/bf03204212	1982	Porac C, Coren S.	Vision Science
Patterns of lateral preference: hand, eye, thumb and clapping	https://doi.org/10.2466/pms.1983.57.3.847	1983	Combs AL.	Vision Science
A developmental study of the relationship between handedness and eyedness as applied to disappearing visual targets	https://doi.org/10.1080/00223980.1984.9923665	1984	Mandes E, Strauss J.	Vision Science
Monocular Asymmetries in Vision: A Phenomenal Basis for Eye Signature	https://doi.org/10.1037/h0080872	1984	C Porac,S Coren	Vision Science
Sighting dominance and egocentric localization	https://doi.org/10.1016/0042-6989(86)90057-x	1986	Porac C, Coren S.	Vision Science
Sighting dominance and utrocular discrimination	https://doi.org/10.3758/BF03207075	1986	Porac, C; Coren, S	Vision Science
Pattern reversal visual evoked potentials (white-black- and colour-black-PVEPs) in the study of eye dominance	https://doi.org/10.1007/BF00377421	1987	Taghavy A, Kügler CF.	Vision Science

Title	DOI	Year	Authors	Category
Binocular accommodation reaction and response times for normal observers	https://doi.org/10.1111/j.1475-1313.1989.tb00839.x	1989	Heron G, Winn B.	Vision Science
Handedness, cerebral lateralization, and measures of latent left-handedness	https://doi.org/10.3109/00207458908986203	1989	Bryden MP.	Vision Science
The relationship between eye position and egocentric visual direction	https://doi.org/10.3758/BF03212230	1991	Barbeito, R; Simpson, TL	Vision Science
Dynamics of accommodative vergence movements controlled by the dominant and nondominant eye	https://doi.org/10.1111/j.1600-0420.1995.tb00034.x	1995	Han, Y; Seideman, M; Lennerstrand, G	Vision Science
Handedness and eye-dominance: A Meta-analysis of Their Relationship	https://doi.org/10.1080/713754206	1996	McManus, IC; Bryden, MP; Bourassa, DC	Vision Science
Aperture based selection for immersive virtual environments	https://doi.org/10.1145/237091.237105	1996	A. Forsberg, K. Herndon, R. Zeleznik	HCI
Viewing difficulties with head-mounted aids for mechanical assembly using nearby virtual objects	https://doi.org/10.1109/ETFA.1996.573732	1996	S.R. Ellis, F. Breant, B. Menges, R. Jacoby, B.D. Adelstein,	HCI
Characteristics of dynamic accommodation responses: comparison between the dominant and non-dominant eyes	https://doi.org/10.1016/S0275-5408(96)00032-4	1997	Ibi K.	Vision Science
Ocular dominance: some family data	https://doi.org/10.1080/713754254	1997	Reiss MR.	Vision Science
Image plane interaction techniques in 3D immersive environments	https://doi.org/10.1145/253284.253303	1997	J. S. Pierce, A. S. Forsberg, M. J. Conway, S. Hong, R. C. Zeleznik, M. R. Mine	HCI
Ocular dominance effects on the application of monocular, occluding head-mounted displays	https://doi.org/10.1177/107118139704100213 2	1997	Kancler, DE; Quill, LL	HCI

Title	DOI	Year	Authors	Category
Selection using a one-eyed cursor in a fish tank VR environment	https://doi.org/10.1145/267135.267136	1997	C. Ware, K. Lowther	HCI
Consistency of performance on eyedness tasks	https://doi.org/10.1111/j.2044-8295.1998.tb02671.x	1998	Osburn, D. M., & Klingsporn, M. J.	Vision Science
Early studies of eye dominances	https://doi.org/10.1080/713754296	1998	Wade N.J.	Vision Science
Eye-dominance, writing hand, and throwing hand	https://doi.org/10.1080/713754334	1999	I.C. McManus, C. Porac, M.P. Bryden, R. Boucher	Vision Science
Quantitative assessment of five behavioural laterality measures: distributions of scores and intercorrelations among right-handers	https://doi.org/10.1080/713754344	1999	Papousek I, Schulter G.	Vision Science
Sensorimotor performance as a function of eye dominance and handedness	https://doi.org/10.2466/PMS.88.2.424-426	1999	Coren, S	Vision Science
Predicting combinations of left and right asymmetries	https://doi.org/10.1016/S0010-9452(08)70534-3	2000	Annett M.	Vision Science
Dynamic asymmetries in convergence eye movements under natural viewing conditions	https://doi.org/10.1016/s0021-5155(01)00405-1	2001	Kawata H(1), Ohtsuka K.	Vision Science
Mandibular deviations in TMD and non-TMD groups related to eye dominance and head posture	https://doi.org/10.17796/jcpd.25.2.j7171238p2413611	2001	Pradham N.S.; White G.E.; Mehta N.; Forgione A.	Vision Science
Ocular dominance reverses as a function of horizontal gaze angle	https://doi.org/10.1016/s0042-6989(01)00079-7	2001	Khan AZ, Crawford JD.	Vision Science
Vision research: losing sight of eye dominance	https://doi.org/10.1016/s0960-9822(01)00496-1	2001	Carey DP.	Vision Science

Title	DOI	Year	Authors	Category
Evaluation of eye-dominance effects on target-acquisition tasks using a head-coupled monocular HMD	https://doi.org/10.1177/154193120104501826	2001	T. LaFleur , Mark H. Draper, Heath A. Ruff	HCI
Measuring visual axis as an independent variable from a fixation distance	https://doi.org/10.1109/ICSMC.2002.1175559	2002	T. Hayami, K. Shidoji, S. Horimoto,H. Matsugashita,	HCI
Rivalry and interference with a head-mounted display	https://doi.org/10.1145/568513.568516	2002	Laramee, Robert S. and Ware, Colin	HCI
Coordinating one hand with two eyes: optimizing for field of view in a pointing task	https://doi.org/10.1016/s0042-6989(02)00569-2	2003	Khan AZ, Crawford JD.	Vision Science
Ocular kinematics and eye-hand coordination	https://doi.org/10.1076/stra.11.1.33.14094	2003	Crawford J.D.; Henriques D.Y.P.; Medendorp W.P.; Khan A.Z.	Vision Science
Ocular prevalence versus ocular dominance	https://doi.org/10.1016/s0042-6989(03)00121-4	2003	Kommerell G, Schmitt C, Kromeier M, Bach M.	Vision Science
What does the dominant eye dominate? A brief and somewhat contentious review	https://doi.org/10.3758/bf03194802	2003	Mapp AP, Ono H, Barbeito R.	Vision Science
Effects of dominant and nondominant eyes in binocular rivalry	https://doi.org/10.1097/01.opx.0000135085.54136.65	2004	Handa T, Mukuno K, Uozato H, Niida T, Shoji N, Shimizu K.	Vision Science
Relative image size, not eye position, determines eye dominance switches	https://doi.org/10.1016/j.visres.2003.09.029	2004	Banks MS, Ghose T, Hillis JM.	Vision Science
A pointing method of an object in real space using dominant eye's view field	https://doi.org/10.1109/TEXCRA.2004.1425004	2004	Y. Mitsudo,E. Miyazaki,M. Idesawa,	HCI

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Ocular dominancy in conjugate eye movements at reading distance	https://doi.org/10.1016/j.neures.2005.03.013	2005	A. Oishi, S. Tobimatsu, K. Arakawa, T. Taniwaki, and J.ichi Kira.	Vision Science
Assessment of ocular stereovision prevalence and eye dominance stability	https://doi.org/10.1117/12.639413	2005	Ozolinsh M.; Anisko K.; Ikaunieks G.; Krumina G.	Vision Science
Effects of eye dominance in visual perception	https://doi.org/10.1016/j.ics.2005.05.006	2005	Shneor E.; Hochstein S.	Vision Science
Eye preference within the context of binocular functions	https://doi.org/10.1007/s00417-005-1128-7	2005	Ehrenstein, W.H.,Arnold-Schulz-Gahmen, B.E., Jaschinski,W.	Vision Science
Integration, segregation, and binocular combination	https://doi.org/10.1364/josaa.22.000038	2005	Mansouri B(1), Hess RF, Allen HA, Dakin SC.	Vision Science
Eye dominance effects in feature search	https://doi.org/10.1016/j.visres.2006.08.006	2006	Shneor E, Hochstein S.	Vision Science
Ocular prevalence and stereoacuity	https://doi.org/10.1111/j.1475-1313.2005.00344.x	2006	M. Kromeier, S. P. Heinrich, M. Bach, and G. Kommerell,	Vision Science
The effect of binocular and monocular distractors on saccades in participants with normal binocular vision	https://doi.org/10.1016/j.visres.2005.09.012	2006	Griffiths H., Whittle J, Buckley D.	Vision Science
3D TV using MPEG-2 and H.264 view coding and autostereoscopic displays	https://doi.org/10.1145/1180639.1180747	2006	L. Christodoulou, L. M. Mayron, H. Kalva, O. Marques, B. Furht	HCI
Design and evaluation of a 3D video system based on H.264 view coding	https://doi.org/10.1145/1378191.1378207	2006	H. Kalva, L. Christodoulou, L. M. Mayron, O. Marques, B. Furht	HCI

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Development of EOG-Based Communication System Controlled by Eight-Directional Eye Movements	https://doi.org/10.1109/IEMBS.2006.259914	2006	Kenji Yamagishi,Junichi Hori,Michio Miyakawa,	HCI
Perceived quality of compressed stereoscopic images: Effects of symmetric and asymmetric JPEG coding and camera separation	https://doi.org/10.1145/1141897.1141899	2006	P. Seuntiens, L. Meesters, W. Ijsselsteijn	HCI
The absence of lateral congruency between sighting dominance and the eye with better visual acuity	https://doi.org/10.1111/j.1475-1313.2006.00414.x	2007	Pointer JS.	Vision Science
Evaluation of 3DTV service using asymmetric view coding based on MPEG-2	https://doi.org/10.1109/3DTV.2007.4379454	2007	Kalva, H; Christodoulou, L; Furht, B	HCI
Eye dominance effects in conjunction search	https://doi.org/10.1016/j.visres.2008.04.021	2008	Shneor E, Hochstein S.	Vision Science
Results of ocular dominance testing depend on assessment method	https://doi.org/10.1016/j.jaapos.2008.01.017	2008	Rice ML, Leske DA, Smestad CE, Holmes JM.	Vision Science
A new method to assess eye dominance	NA	2008	Valle-Inclan, F; Blanco, MJ; Soto, D; Leiros, L	Vision Science
Withindows: A framework for transitional desktop and immersive user interfaces	https://doi.org/10.1109/3DUI.2008.4476584	2008	Hill, A; Johnson, A	HCI
Lateralized effects of hand and eye on anticipatory postural adjustments in visually guided aiming movements	https://doi.org/10.1016/j.neulet.2009.06.044&2009	Ypsilanti A.; Hatzitaki V.; Grouios G.		Vision Science

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Study on dominant eye measurement	NA	2009	Gündogan, N., Yazici, AC, Simsek, A	Vision Science
When the wheels touch earth and the flight is through, pilots find one eye is better than two	https://doi.org/10.1117/12.818901	2009	Valimont B.; Wise J.A.; Nichols T.; Best C.; Suddreth J.; Cupero F.	HCI
Effects of visual environment complexity on saccade performance in humans with different functional asymmetry profiles	https://doi.org/10.1007/s11055-010-9342-0	2010	Kolesnikova OV, Tereshchenko LV, Latanov AV, Shulgovskii VV.	Vision Science
Ocular dominance and balance performance in healthy adults	https://doi.org/10.1016/j.gaitpost.2009.11.015	2010	Gandelman-Marton R(1), Arlazoroff A, Dvir Z.	Vision Science
Quantifying sensory eye dominance in the normal visual system: a new technique and insights into variation across traditional tests	https://doi.org/10.1167/iovs.10-5549	2010	Li J, Lam CS, Yu M, Hess RF, Chan LY, Maehara G, Woo GC, Thompson B.	Vision Science
Which Factors Affect Hand Selection in Adults? Combined Effects of Ocular Dominance, Task Demand and Object Location	https://doi.org/10.2478/v10078-010-0046-x	2010	Rezaee M.; Shojaee M.; Ghasemi A.; Moghaddam A.; Momeni M.	Vision Science
Dynamic Visual Acuity (DVA) Binocular Summation and DVA Performance Factors	https://doi.org/10.1109/JDT.2010.2045635	2010	Masaki Emoto,	HCI
Thoughts on ocular dominance - Is it actually a preference?	https://doi.org/10.1097/ICL.0b013e31820e0bdf	2011	Laby DM, Kirschen DG.	Vision Science
Ocular dominance stability and reading skill: a controversial relationship	https://doi.org/10.1097/OPX.0b013e318229635a	2011	Zeri F, De Luca M, Spinelli D, Zoccolotti P.	Vision Science
Relative contributions of the two eyes to perceived egocentric visual direction in normal binocular vision	https://doi.org/10.1016/j.visres.2011.02.023	2011	Sridhar, D; Bedell, HE	Vision Science

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2D Touching of 3D Stereoscopic Objects	https://doi.org/10.1145/1978942.1979142	2011	Valkov, D; Steinicke, F; Bruder, G; Hinrichs, K	HCI
Parameter Estimation Variance of the Single Point Active Alignment Method in Optical See-Through Head Mounted Display Calibration	https://doi.org/10.1109/VR.2011.5759432	2011	Axholt, M; Skoglund, MA; O'Connell, SD; Cooper, MD; Ellis, SR; Ynnerman, A	HCI
Binocular image dominant mechanism	https://doi.org/10.1109/IGARSS.2012.6350406	2012	Jing-Jing Ge,Zhao-Rong Lin,Da-Kai Zhu,	Vision Science
Sighting versus sensory ocular dominance	https://doi.org/10.1016/j.optom.2012.03.001	2012	Pointer J.S.	Vision Science
Beyond stereo: an exploration of unconventional binocular presentation for novel visual experience	https://doi.org/10.1145/2207676.2208638	2012	H. Zhang, X. Cao, S. Zhao	HCI
Effects of dominance and laterality on iris recognition	https://doi.org/10.1109/CVPRW.2012.6239215	2012	Amanda Sgroi, Kevin W. Bowyer, Patrick Flynn	HCI
Looking at eye dominance from a different angle: is sighting strength related to hand preference?	http://dx.doi.org/10.1016/j.cortex.2012.11.011	2013	Carey DP, Hutchinson CV.	Vision Science
Ocular dominance and visual function testing	http://dx.doi.org/10.1155/2013/238943	2013	D. Lopes-Ferreira, H. Neves, A. Queiros, M. Faria-Ribeiro, S. C. Peixoto-de-Matos, and J. M. González-Méijome	Vision Science
Relation of eye dominancy with color vision discrimination performance ability in normal subjects	https://doi.org/10.3980/j.issn.2222-3959.2013.05.34	2013	B.Koçtekin,N.Ü. Güdogan, A.G.K. Altıntaş, A.C. Yazıcı.	Vision Science

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Binocular cursor: enabling selection on transparent displays troubled by binocular parallax	https://doi.org/10.1145/2470654.2466433	2013	J. Hyub Lee, S-H Bae	HCI
Evaluation of mono/binocular depth perception using virtual image display	https://doi.org/10.1007/978-3-642-39342-6_53	2013	Yang-Mao S.-F.; Lin Y.-T.; Lin M.-H.; Zeng W.-J.; Wang Y.-L.	HCI
Fundamental research on three-dimensional pointing movement in consideration of change of X- and Z-axis rotation angles	NA	2013	Atsuo Murata,Takehito Hayami,Takanori Akiyama,	HCI
Pointing at 3d target projections with one-eyed and stereo cursors	https://doi.org/10.1145/2470654.2470677	2013	R.J. Teather, W. Stuerzlinger	HCI
Effects of ocular dominance on contrast sensitivity in middle-aged people	https://doi.org/10.1155/2014/903084	2014	Pekel G, Alagöz N, Pekel E, Alagöz C, Yılmaz OF.	Vision Science
The effect of contrast on monocular versus binocular reading performance	https://doi.org/10.1167/14.5.8	2014	Johansson J., Pansell T., Ygge J., Seimyr G.	Vision Science
Visual aspects advanced sensors and helmet-mounted displays	https://doi.org/10.1017/S0001924000009040	2014	Morgan-Warren, PJ; Woodcock, M	Vision Science
Effect of eye dominance on the perception of stereoscopic 3D video	https://doi.org/10.1109/ICIP.2014.7025704	2014	Banitalebi-Dehkordi, A; Pourazad, MT; Nasiopoulos, P	HCI
Fishtank fitts: a desktop VR testbed for evaluating 3D pointing techniques	https://doi.org/10.1145/2559206.2574810	2014	R. J. Teather, W. Stuerzlinger, A. Pavlovych	HCI
Efficient Stereo Rendering of Large 3D Datasets Based on Binocular Suppression	https://doi.org/10.1109/35021BIGCOMP.2015.7072855	2015	Shin, IK; Kim, HJ; Choi, SM; Rhee, SM	HCI

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Exploiting Binocular Rivalry: Presenting Different Contents on Dominant and Non-dominant Eyes	https://doi.org/10.1109/ISMARW.2015.14	2015	Jinhyun Park,Jun Park,	HCI
Factors Affecting Mouse-Based 3D Selection in Desktop VR Systems	https://doi.org/10.1145/2788940.2788946	2015	R.J. Teather, W. Stuerzlinger	HCI
Perceptually Reduced Crosstalk by Modifying Binocular Images Depending on Dominant Eye	https://doi.org/10.1109/JDT.2015.2399506	2015	Jong-Man Kim,Seung-Ryul Kim,Minkoo Kim,Joohwan Kim,Seung-Woo Lee,	HCI
Quality Prediction of Asymmetrically Distorted Stereoscopic 3D Images	https://doi.org/10.1109/TIP.2015.2446942	2015	Jiheng Wang,Abdul Rehman,Kai Zeng,Shiqi Wang,Zhou Wang,	HCI
How Eye Dominance Strength Modulates the Influence of a Distractor on Saccade Accuracy	https://doi.org/10.1167/iovs.15-18428	2016	Tagu, J; Doré-Mazars, K; Lemoine-Lardennois, C; Vergilino-Perez, D	Vision Science
3D Blur Discrimination	https://doi.org/10.1145/2896453	2016	M. M. Subedar, L. J. Karam	HCI
Accuracy of interpreting pointing gestures in egocentric view	https://doi.org/10.1145/2971648.2971687	2016	D. Akkil, P. Isokoski	HCI
Effect of Ocular Dominance on Touch Position	https://doi.org/10.1109/JDT.2016.2553219	2016	Seung-Ryeol Kim,Jong-Man Kim,Joohwan Kim,Seung-Woo Lee,	HCI
Sighting ocular dominance magnitude varies with test distance	https://doi.org/10.1111/cxo.12627	2018	Ho, R; Thompson, B; Babu, RJ; Dalton, K	Vision Science
Comparing input methods and cursors for 3D positioning with head-mounted displays	https://doi.org/10.1145/3225153.3225167	2018	J. Sun, W. Stuerzlinger, B. E. Riecke	HCI

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EyePACT: Eye-Based Parallax Correction on Touch-Enabled Interactive Displays	https://doi.org/10.1145/3161168	2018	M. Khamis, D. Buschek, T. Thieron, F. Alt, A. Bulling	HCI
FocusVR: Effective 8 Usable VR Display Power Management	https://doi.org/10.1145/3264952	2018	T. Kiat Wee, E. Cuervo, R. Balan	HCI
Optimized Viewport Dependent Streaming of Stereoscopic Omnidirectional Video	https://doi.org/10.1145/3210424.3210437	2018	D. Naik, I. D. D. Curcio, H. Toukomaa	HCI
Projective Windows: Bringing Windows in Space to the Fingertip	https://doi.org/10.1145/3173574.3173792	2018	J. Hyub Lee, S-G. An, Y. Kim, S-H Bae	HCI
The Effect of Offset Correction and Cursor on Mid-Air Pointing in Real and Virtual Environments	https://doi.org/10.1145/3173574.3174227	2018	S. Mayer, V. Schwind, R. Schweigert, N. Henze	HCI
Psychophysical Tests Do Not Identify Ocular Dominance Consistently	https://doi.org/10.1177/2041669519841397	2019	García-Pérez, MA; Peli, E	Vision Science
Some binocular advantages for planning reach, but not grasp, components of prehension	https://doi.org/10.1007/s00221-019-05503-4	2019	Grant S, Conway ML.	Vision Science
Monocular Viewing Protects Against Cybersickness Produced by Head Movements in the Oculus Rift	https://doi.org/10.1145/3359996.3364699	2019	S. Palmisano, L. Szalla, J. Kim	HCI
Eye dominance modulates visuospatial attention	https://doi.org/10.1016/j.neuropsychologia.2019.107314	2020	Schintu, S; Chaumillon, R; Guillaume, A; Salemme, R; Reilly, KT; Pisella, L; Farnè, A	Vision Science
The Dominant Eye: Dominant for Parvo- But Not for Magno-Biased Stimuli?	https://doi.org/10.3390/vision4010019	2020	Foutch BK, Bassi CJ	Vision Science
Eye-dominance-guided Foveated Rendering	https://doi.org/10.1109/TVCG.2020.2973442	2020	Xiaoxu Meng,Ruofei Du,Amitabh Varshney,	HCI

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The Critical Role of Stereopsis in Virtual and Mixed Reality Learning Environments	https://doi.org/10.1002/ase.1928	2020	Wainman B, Pukas G, Wolak L, Mohanraj S, Lamb J, Norman GR.	HCI
The effect of ocular dominance on decision making in a virtual environment	https://doi.org/10.1007/978-3-030-51828-8_88	2020	Suk H.J.; Kim S.J.	HCI
Gaze+Hold: Eyes-only Direct Manipulation with Continuous Gaze Modulated by Closure of One Eye	https://doi.org/10.1145/3448017.3457381	2021	A. Ramirez Ramirez Gomez, C. Clarke, L. Sidenmark, H. Gellersen	HCI
Visual perception study on the image quality of binocular tone mapping	https://doi.org/10.1002/sdtp.15262	2021	Xia Z.; Song Y.; Ma F.; Zhang B.; Hu F.	HCI
Comparing accommodative function between dominant and non-dominant eye	https://doi.org/10.18231/j.ijceo.2022.085	2022	Jaya Priya S.; Ikram S.S.; Puri S.K.	Vision Science
A Replication Study to Measure the Perceived Three-Dimensional Location of Virtual Objects in Optical See Through Augmented Reality	https://doi.org/10.1109/VRW55335.2022.00249	2022	Farzana Alam Khan,Mohammed Safayet Arefin,Nate Phillips,J. Edward Swan,	HCI
A Better Approach of Assessing Laterality by Using Combined Foot and Eye Dominance Scale in Mentally Healthy Subjects	https://doi.org/10.2478/amb-2023-0017	2023	Akabalieva K.; Kotetarov V.; Beshkov A.	Vision Science
Attentional Sampling between Eye Channels	https://doi.org/10.1162/jocn_a_02018	2023	Daniele Re,Golan Karvat,Ayelet N. Landau,	Vision Science
Eye-Perspective View Management for Optical See-Through Head-Mounted Displays	https://doi.org/10.1145/3544548.3581059	2023	G. Emsenhuber, T. Langlotz, D. Kalkofen, J. Sutton, M. Tatzgern	HCI

Title	DOI	Year	Authors	Category
Selecting Real-World Objects via User-Perspective Phone Occlusion	https://doi.org/10.1145/3544548.3580696	2023	Y. Qin, C. Yu, W. Yao, J. Yao, C. Liang, Y. Weng, Y. Yan, Y. Shi	HCI
The effect of interocular contrast differences on the appearance of augmented reality imagery	https://doi.org/10.1145/3617684	2023	M. Wang, J. Ding, D. M. Levi, E. A. Cooper	HCI
Examining the Relationship Between the Dominant Eye and the Dominant Hand	http://dx.doi.org/10.32598/fdj.6.233.1	2923	Almasi A, Mirzajani A, Abolghasemi J, Rahmani S.	Vision Science

A.3 Predictive Model Additional Figure

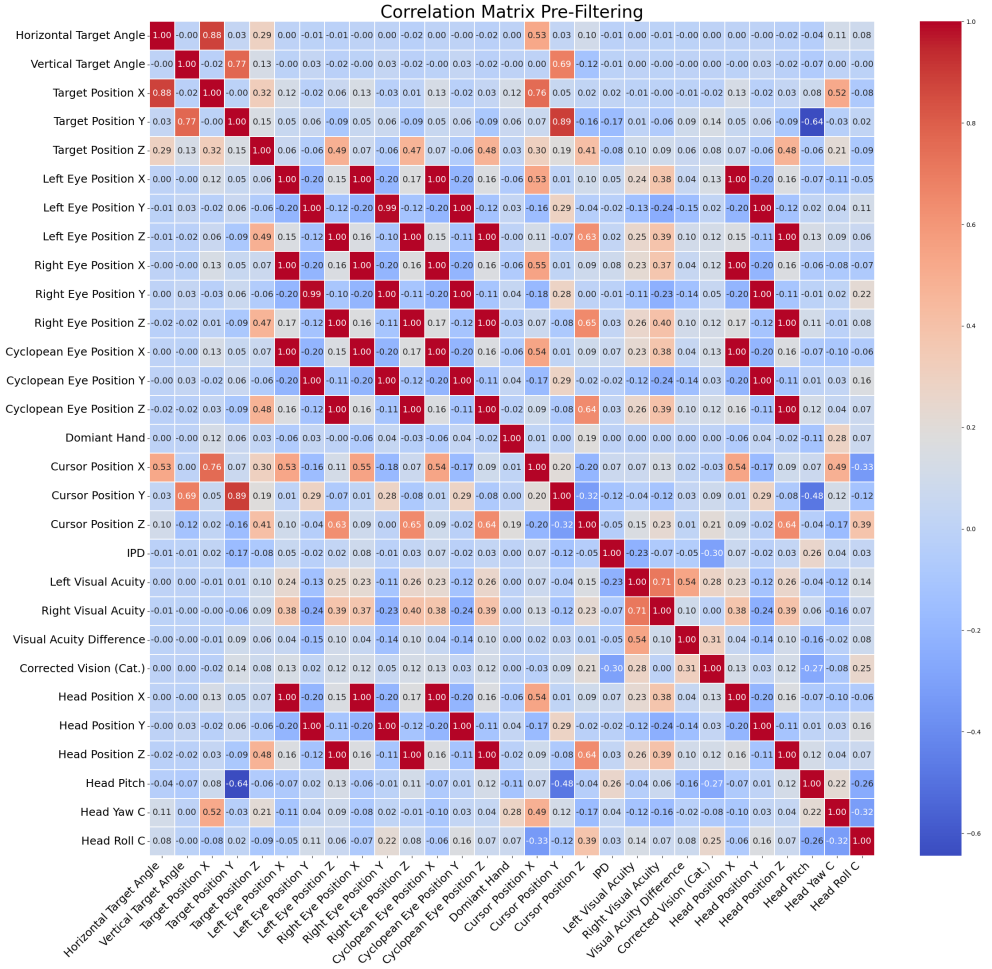

Figure A.1: Correlation matrix of all features pre-filtering. Features with correlations above a 0.8 Pearson correlation threshold were excluded from the further feature selection process.

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