Investigation into Use of Vision and Proprioception in Upper Limb Movements in Virtual Reality

by

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DISSERTATION ABSTRACT

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Upper limb reaching movements are primarily planned and executed using two sensory inputs: vision and proprioception. The optimal integration theory suggests that the central nervous system weights these inputs in a statistically optimal manner to maximize movement accuracy. However, this relative reliance on each sense can shift depending on various contextual factors, such as the quality of sensory inputs, the demands of the task, and inherent differences between individuals. Virtual reality (VR) provides a valuable tool to study these mechanisms, as it allows researchers to precisely manipulate visual feedback while minimizing external confounding variables in a controlled 3D environment.

This dissertation investigates how vision and proprioception are integrated during upper limb movements, focusing on the effects of limb dominance, sex, and athletic background. It includes six chapters, with Chapter I serving as an introduction to the theoretical background and study objectives. Chapters II and III focus on developing two VR-based sensorimotor tests: (1) an active shoulder joint position sense (JPS) test, in which participants replicate static arm-elevation angles, and (2) a dynamic reaching test, in which participants reach to "intercept" a target moving toward them under manipulated visual conditions. Chapter IV uses the JPS test to examine how limb side and population differences (males vs. females, athletes vs. non-athletes) affect sensory integration patterns and movement accuracy. Chapters V and VI apply the dynamic reaching test to examine vision-proprioception integration for upper limb reaching that

requires to track the constantly moving reaching target, again comparing limb side and population differences. Collectively, these studies contribute to our understanding of how movement type (static vs. dynamic), limb side, and individual differences shape multisensory control in upper limb reaching tasks. This dissertation includes both previously published and unpublished co-authored material.

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CHAPTER I

GENERAL INTRODUCTION

1. Background

1.1. Sensory Input in Human Body

Vision and proprioception are the two major sensory inputs the human body utilizes to plan and execute upper limb reaching movements (Block & Bastian, 2010; Lateiner & Sainburg, 2003). Anatomically, optic tracts process visual input such as object movement and hand locations relative to object position in the visual field. This processing begins in the retina, forming the optic nerve as it exits posteriorly from the eyes and enters the brain through the skull and dura (Gupta et al., 2025). Within the brain, the visual cortex located in the occipital lobe at the back of the brain above the cerebellum primarily processes the visual input carried by the optic nerve (Huff et al., 2025). Each hemisphere processes vision from the contralateral visual field, meaning the right hemisphere handles visual input from the left eye and vice versa (Huff et al., 2025).

Proprioception refers to "the perception of joint and body movement as well as the position of the body or body segments in space" (Han et al., 2016). For example, individuals without motor impairment can touch their nose even with their eyes closed because proprioception guides the hand without visual input. Primary sources of proprioceptive input include muscle spindles, Golgi tendon organs (GTOs), joint receptors, cutaneous receptors, and the vestibular system (Henry & Baudry, 2019; Proske & Gandevia, 2009). Among these, muscle spindles attached to muscle fibers and GTOs located at the junction of muscle fibers and tendons play major roles in providing proprioceptive feedback to the central nervous system (CNS) (Proske & Gandevia, 2009). Proprioceptive input from these receptors enters the dorsal column of the spinal cord, ascends contralaterally, and reaches the cerebellum (Ives, 2013). Subsequently, the proprioceptive input is transmitted to the somatosensory cortex in the parietal lobe, located just posterior to the central sulcus (Raju & Tadi, 2025).

After vision and proprioception are processed in the visual and somatosensory cortices, respectively, they are integrated primarily in the posterior parietal cortex and ventral premotor cortex (Limanowski & Blankenburg, 2016). Numerous theoretical frameworks have been proposed for how the brain integrates sensory information, including vision and proprioception (Camponogara, 2023). One of the most widely adopted theories in motor control studies is the optimal integration theory (Berger & Bülthoff, 2009; Block & Bastian, 2011a; Ernst & Banks, 2002; Lateiner & Sainburg, 2003). This theory suggests that sensory information is integrated and weighted statistically optimally to obtain the most accurate estimate of body position in the environment (Ernst & Banks, 2002; Hayashi et al., 2020; van Beers et al., 2002). Factors influencing sensory weighting include sensory quality, movement type, limb side, and individual biase/preference toward each sensory (Block & Bastian, 2011b; Ernst & Banks, 2002). Consequently, upper limb movements vary as the brain optimizes its reliance on vision and proprioception based on specific situations and environments (Kumawat et al., 2022; Morehead et al., 2017; Spitzley & Karduna, 2022). Generally, vision dominates in arm-reaching tasks by providing essential information about external objects and spatial positioning, whereas proprioception aids in fine adjustments for movement accuracy (Goodman & Tremblay, 2021; van Beers et al., 2002).

1.2. Motor Control Patterns Among Populations

Population differences significantly influence the integration of vision and proprioception, as the motor control system adapts specifically to individual experiences and physiological changes. In a previous study examining hand-reaching accuracy, younger adults showed shorter movement durations and smaller spatial errors compared to older adults, regardless of whether vision was provided or occluded (Chaput & Proteau, 1996). Notably, despite having lower proprioceptive accuracy, older adults relied more heavily on proprioceptive input than younger adults during reaching tasks (Chaput & Proteau, 1996). Another study reported that stroke survivors generally exhibit impaired proprioception, and their inter-limb position matching accuracy improved with visual feedback of their limb position only for some individuals, likely due to variability in stroke-damaged brain areas affecting visual processing (Herter et al., 2019). These findings underscore significant individual variability in motor control based on demographic background and experiences.

The fine coordination of vision and proprioception is crucial for baseball and softball athletes, as they are required to accurately hit and catch a ball. However, to our knowledge, no study has investigated the multisensory integration mechanism of baseball or softball athletes in upper limb reaching movements, while many of them reported independent association of vision or proprioception with the sport performance, the risk of injury, or population differences between the athletes and non-athletes (Chen et al., 2021; Ettinger et al., 2017; Freeston et al., 2015; Kirschen & Laby, 2021; Klemish et al., 2018; Laby et al., 2018; Marsh et al., 2004; Myers et al., 2006; Myrick et al., 2019). Prior research has shown that baseball players exhibit superior reaching accuracy compared to non-athletes in tasks involving dynamically moving targets on a touchscreen (Chen et al., 2021). Within the baseball athlete cohort, vision appears to differentiate elite players from less successful ones. Nearly 70% of prospective athletes with good or moderate visual function, assessed using a vision score scale, were drafted into Major League Baseball, whereas only one in approximately 500 athletes with poor visual function was selected (Kirschen & Laby, 2021). In contrast, proprioception does not seem to be as strongly correlated with sports performance as studies have found no significant relationships between proprioceptive function and pitching accuracy or velocity (Freeston et al., 2015; Marsh et al., 2004; Myrick et al., 2019). However, the shoulder (glenohumeral) joint proprioception of the baseball athletes is altered partially due to an increased laxity of the glenohumeral joint and accumulated microtrauma to the joint capsules by repetitive overhead throwing movements (Myers et al., 2006). Similarly, softball athletes demonstrated greater reaching errors than control participants in shoulder joint repositioning tasks (Dover et al., 2003). These findings suggest that throwing athletes may exhibit unique visual and proprioceptive functions compared to non-athletes, warranting further research into their multisensory integration mechanisms. In addition, non-throwing arm of these athletes may have enhanced vision-proprioception integration as they have extensive experience of catching the ball. Motor learning is known to occur specific to situations and movement patterns (Paillard, 2017; Proteau & Isabelle, 2002). Although speculative, repetitive ball catching experience could potentially result in distinctive reaching patterns compared to non-athletes.

Sex differences in vision-proprioception integration remain unclear due to conflicting findings. Some studies suggest males exhibit worse proprioception than females (Vafadar et al., 2015), while others report no significant sex differences in joint position matching tasks (Echalier et al., 2019). However, sex differences become more evident in complex reaching tasks involving dynamic visual input, with females typically showing lower accuracy when reaching for dynamically moving targets or multiple static targets using both arms simultaneously

(McGivern et al., 2012; Mickevičienė et al., 2011). These differences might be due to distinct neural processing pathways for visual input as men predominantly utilize the dorsal stream of. The visual cortex specialized for analyzing object movement, whereas women rely more on the ventral stream specialized for object characteristics such as its color and shape (Goodale & Milner, 1992; McGivern et al., 2012; Vanston & Strother, 2017). Investigating these sex differences in reaching tasks involving dynamically moving targets could further clarify sex-specific sensory integration mechanisms.

Overall, population-specific differences significantly influence vision-proprioception integration. Baseball and softball athletes may possess better visual tracking compared to non-athletes, even though their throwing arm might have altered proprioception due to repetitive high-intensity throwing. Sex differences in vision-proprioception integration likely depend on the complexity and type of reaching task, with pronounced differences potentially linked to visual input processing streams in the visual cortex.

1.3. Reaching Test Modality

Reaching tests can be categorized into static and dynamic types based on whether the reaching targets involved are stationary or moving. Static reaching tasks involve reaching for a fixed target location displayed on a computer or positioned in real-world 3D space. Prior research indicates the relative contribution of vision and proprioception during static tasks depends on individuals' conscious control of sensory reliance (Block & Bastian, 2010; Morehead et al., 2017), the specific plane of arm movement (e.g., anterior-posterior or medial-lateral) (Klein et al., 2018; van Beers et al., 2002), and population characteristics (Chen et al., 2021; Rand et al., 2013). A common static task is the joint position sense (JPS) test, where subjects match or reposition a limb based on contralateral or ipsilateral reference positions (Roach et al., 2023). However, static tasks may not accurately capture the motor skills of baseball and softball athletes, whose performance depends on interacting with dynamically moving objects in three-dimensional (3D) environments. Additionally, static reaching tasks report inconsistent results regarding sex differences in sensory integration (Echalier et al., 2019; Mickevičienė et al., 2011; Vafadar et al., 2015).

Dynamic reaching tasks, conversely, involve targets that move. These tasks are typically performed on a horizontal 2D plane, either on computer screens or customized setups creating physically moving targets (Fialho & Tresilian, 2017; Morehead et al., 2017; Schroeger et al., 2021). Tasks typically require to accurately hit the moving target with a hand. Dynamic tests evaluate not only spatial accuracy but also temporal accuracy, reaction times, and hand velocities (Mickevičienė et al., 2011; Schroeger et al., 2021). Despite their increased complexity compared to static tasks, 2D dynamic reaching tasks may lack validity for understanding vision-proprioception integration mechanisms in baseball and softball athletes. This is because their motor learning for dynamic reaching primarily occurs through experiences like ball catching and hitting in three-dimensional (3D) environments, where objects move toward them predominantly in the anterior-posterior plane. Consequently, typical dynamic reaching tasks conducted in the 2D horizontal plane may not suitably replicate the conditions necessary for researchers to accurately examine how these athletes integrate sensory inputs and execute reaching movements. Previous research has shown that females demonstrate lower spatial reaching accuracy and slower response times compared to males in both 2D and 3D dynamic reaching tests (Lipps et al., 2013; McGivern et al., 2012; Mickevičienė et al., 2011). In contrast, static tasks have yielded mixed results regarding sex differences. Therefore, it could be beneficial to further investigate sex differences by having male and female participants perform both common static and dynamic reaching tasks comprehensively. Such thorough assessments would help clarify sex-related variations in reaching accuracy and shed light on the neural mechanisms underpinning these motor control differences.

1.4. Virtual Reality Systems

Virtual reality (VR) technology first emerged in the 1960s and has significantly expanded since then, growing from a market size of US $7.3 billion in 2018 and projected to reach US $120.5 billion by 2026 (Wohlgenannt et al., 2020). Consumer VR platforms such as Meta's Oculus Quest, HTC's VIVE, and Apple's Vision Pro have become increasingly popular in recent years. These VR systems typically utilize head-mounted displays to project immersive visual environments, providing users with a realistic sense of "being there." While most VR use has historically been in video gaming, VR systems are now utilized across various domains, including medical surgery and dental practice simulations, health screenings for insurance assessments, and even talent identification in soccer through VR-based movement tasks (Wohlgenannt et al., 2020). In the realm of scientific research, VR has primarily been applied in education and medicine to understand social behaviors and evaluate the effectiveness of VR-based training. Research utilizing VR technology has notably increased since around 2015.

In motor control research specifically, VR has significantly advanced the study of vision-proprioception integration by enabling precise control and manipulation of visual stimuli within realistic 3D environments, while maintaining acceptable data accuracy (Spitzley & Karduna, 2019). Unlike traditional tools such as prism goggles (Hansen et al., 2007) and 2D computer displays (Morehead et al., 2017), VR provides a more sophisticated platform for investigating multisensory integration. VR-based reaching tasks can simulate real-world scenarios, such as tracking the trajectory of a baseball, while minimizing the influence of external factors that are difficult to control in the real-world 3D environment. Dynamic reaching tasks, like ball-catching experiments, often use physical equipment such as baseball-throwing machines, which causes inconsistencies in ball trajectory and position between trials, potentially affecting participants' reaching movements (Cesqui et al., 2015; Ida et al., 2022). By contrast, VR systems eliminate such variability by consistently reproducing exact ball trajectories and positions between trials. Furthermore, VR allows precise tracking of moving objects frame by frame, as the entire virtual environment is computationally controlled. Both static and dynamic tests conducted in VR environments thus enable researchers to more accurately investigate the motor control mechanisms underlying vision-proprioception integration by analyzing detailed movement patterns during reaching tasks.

Portability represents another key advantage of VR systems. Typically, VR setups require minimal hardware, including only a headset, controllers, a laptop, and connecting cables. This portability is especially valuable when recruiting participants who cannot easily visit research laboratories. For example, patients with limited mobility may find traveling difficult, and athletes may have restricted schedules that prevent travel to distant laboratories. Portable VR systems allow researchers to conveniently conduct testing at locations more accessible to participants. Furthermore, recent advancements have resulted in wireless VR headsets capable of data storage or wireless data transfer through networks such as Bluetooth. Overall, technological advancements continue to enhance the robustness, accuracy, and accessibility of VR systems, making them highly valuable and practical tools for research.

1.5. Summary

The brain and CNS integrate sensory inputs to plan and execute motor commands necessary for specific movements. According to optimal integration theory, vision and proprioception are integrated in a statistically optimal way, maximizing the accuracy of upper limb reaching tasks (Block & Bastian, 2010; Lateiner & Sainburg, 2003). However, different populations may exhibit distinct patterns of vision-proprioception integration and motor execution due to unique training histories and physiological differences. Traditional reaching tests, which commonly involve static tasks or movements conducted in 2D environments, may not adequately represent these inherent motor control patterns. A 3D immersive VR environment that HTC VIVE system provides offers the capability to effectively implement both static and dynamic reaching tasks. VR technology enables accurate and reliable collection of upper limb movement data in 3D environment (Spitzley & Karduna, 2019). Thus, the objectives of this dissertation were: 1) to investigate the feasibility of implementing a shoulder JPS test (static test) and a ball-catching test (dynamic test) using the HTC VIVE VR system, and 2) to examine population differences in vision-proprioception integration between baseball/softball athletes and non-athlete controls, as well as between males and females, utilizing these static and dynamic reaching tasks.

2. Aims and Overview

This dissertation consists of seven chapters. Chapters II – VI discuss primary research studies and are written in journal research article format. Chapter I provides introductory material to the topics of vision-proprioception integration of throwing sport athletes and upper limb reaching testing in VR environment. Chapter VII summarizes main findings from chapters II – VI. Bridge sections are included to link the content between chapters.

Chapters II and III aim to provide groundwork that establishes fundamental understandings of vision-proprioception integration in static reaching using JPS test and a novel "dynamic reaching test" with physically healthy young individuals being tested. Chapter II were co-authored by Motoki Sakurai, Dr. Kate A. Spitzley, and Dr. Andrew R. Karduna, and previously published in the *Journal of Motor Behavior* under the title "Awareness of Visual Offset Reduces But Does Not Eliminate Joint Repositioning Errors in Virtual Reality". The study design, experimental work including data collection and analysis, and writing was performed by Motoki Sakurai, Drs. Kate A. Spitzley and Andrew R. Karduna provided research mentorship and editorial assistance. Chapter III developed a novel upper limb reaching task in response to a ball moving to participants in VR, mimicking a ball catching situation on baseball and softball fields. The study design, experimental work including data collection and analysis, and writing was performed by Motoki Sakurai, Taylor J. Wilson and Dr. Andrew R. Karduna provided research mentorship and editorial assistance.

Chapter IV uses shoulder JPS test and aims to identify the differences in joint repositioning accuracy and relative contribution of vision and proprioception between throwing athletes and non-athletes as well as females and males. This chapter was co-authored by Motoki Sakurai and Dr. Andrew R. Karduna. The study design, experimental work including data collection and analysis, and writing was performed by Motoki Sakurai, Dr. Andrew R. Karduna provided research mentorship and editorial assistance.

Chapter V and VI use the dynamic reaching test and aims to identify the differences in arm reaching accuracy and relative contribution of vision and proprioception between females and males in chapter V and between throwing athletes and non-athletes in chapter VI. These chapters were co-authored by Motoki Sakurai and Dr. Andrew R. Karduna. The study design, experimental work including data collection and analysis, and writing was performed by Motoki Sakurai, Dr. Andrew R. Karduna provided research mentorship and editorial assistance.

This dissertation advances our understanding of vision-proprioception integration in upper limb reaching tasks, particularly in the context of throwing athletes and sex differences, through the application of VR-based experimental paradigms.

CHAPTER II

AWARENESS OF VISUAL OFFSET REDUCES BUT DOES NOT ELIMINATE JOINT REPOSITIONING ERRORS IN VIRTUAL REALITY

This work is published in volume 56 of the Journal of Motor Behavior in 2024 as "Awareness of Visual Offset Reduces but Does Not Eliminate Joint Repositioning Errors in Virtual Reality" and is co-authored by Motoki Sakurai, Drs. Kate A. Spitzley and Andrew R. Karduna. The study design, experimental work including data collection and analysis, and writing was performed by Motoki Sakurai. Drs. Kate A. Spitzley and Andrew R. Karduna provided research mentorship and editorial assistance.

1. Introduction

Humans integrate multiple sensory inputs in the central nervous system (CNS) to plan and execute active limb movements like reaching for a coffee cup (Apker et al., 2011; Berger & Bülthoff, 2009; Goodman & Tremblay, 2018; Orban de Xivry et al., 2017; Spitzley & Karduna, 2022). Vision and proprioception are the two major sensory inputs that contribute to these movements. (Block & Bastian, 2010). According to the optimal integration theory, the relative contribution of these sensory modalities changes based on many factors, including the quality and quantity of the sensory inputs and conscious effort (Block & Bastian, 2011b; Ernst & Banks, 2002). Reaching movement accuracy is known to be better when both vision and proprioception are available and congruent with each other (Bayramova et al., 2021; Spitzley & Karduna, 2022). However, the misalignment between these senses results in a change in end-position of reaching hands (Hsiao et al., 2022; Morehead et al., 2017; Spitzley & Karduna, 2022).

While vision is a dominant sensory input for planning and initiating accurate movements, proprioception plays a stronger role in making fine adjustments in the body or segment position (Goodman & Tremblay, 2018; Orban de Xivry et al., 2017). Previous studies with subjects seated on a swirl chair reported that vision-only conditions had better self-body-turning task accuracy than proprioception-only conditions. In this task, participants were asked to rotate the chair back to the start position (active rotation) after experimenters rotated the chair from a start position to an end position (passive rotation) (Bayramova et al., 2021; Berger & Bülthoff, 2009; Valori et al., 2020). In a shoulder repositioning accuracy study from our lab using a joint position sense (JPS) test, a 6-9º reaching error in arm repositioning occurred when visual representation of a reaching arm in a virtual reality (VR) environment shifted 8º from the actual arm position, called "visual offset" creating visuo-proprioceptive incongruency (Spitzley & Karduna, 2022). Visuo-proprioceptive incongruency is a situation that visual hand position presented in VR is not aligned with where a participant actually places their hand (8º of visual offset made this incongruency in this case). In that study, participants were not aware of the 8º of visual offset when completing reaching trials. As a result, participants chose to reach to the visual target, rather than the proprioception target. These studies provide evidence that humans tend to prioritize vision over proprioception and can increase the movement accuracy by heavily relying on vision if vision provides accurate information (Apker et al., 2011; Bayramova et al., 2021; Berger & Bülthoff, 2009; Kumawat et al., 2022; Spitzley & Karduna, 2022; Valori et al., 2020).

Awareness of visual offset has the potential to enable humans to consciously reduce the relative weighting of vision in relation to proprioception (Berger & Bülthoff, 2009; Block & Bastian, 2010). In previous studies, participants were instructed to ignore the visual representation of a reaching hand that did not correctly reflect the actual hand movement during motor learning tasks (Hsiao et al., 2022; Morehead et al., 2017). However, over time, participants gradually integrated incorrect virtual hand movements and did not accurately hit proprioceptive targets (Hsiao et al., 2022; Morehead et al., 2017). Another study found that body repositioning accuracy in a self-turning task did not improve, even when participants were aware of visual offset, yet a decrease in the relative weighting on vision with respect to vestibular cue was observed (Berger & Bülthoff, 2009). The CNS appears to have conscious control over the relative weighting of each sensory input to some extent, but this control is not sufficient to reduce body/segment repositioning errors. Currently, little is known about the optimal integration of vision and proprioception for a shoulder repositioning task where humans are aware of a visual offset and instructed to ignore vision. Given the previous findings that the conscious effort to down weight faulty visual cues did not reduce the single hand reaching accuracy and the body repositioning accuracy (Berger & Bülthoff, 2009; Hsiao et al., 2022; Morehead et al., 2017), a shoulder JPS that involves single arm repositioning will strengthen the literature around the optimal integration theory and its relationship with conscious effort to down weight vision. Although different types of shoulder proprioception test are proposed, single arm repositioning requires more involvement of vision over proprioception when both senses are present (Spitzley & Karduna, 2022). This could be a reason that vision was difficult to consciously ignore in the previous studies (Hsiao et al., 2022; Morehead et al., 2017). The current study aims at following up our previous study that found the dominance of vision over proprioception in JPS test when no instruction about offset was provided (Spitzley & Karduna, 2022).

Fully immersive VR is a promising technology that has been growing rapidly. It creates an environment where vision can be independently manipulated in isolation from proprioception in three-dimensional (3D) space (Spitzley & Karduna, 2022). Shoulder joint repositioning accuracy has been traditionally tested with conditions where the eyes are either open or closed (Ager et al., 2017). VR environments allow researchers to test not only the effect of visual occlusion on shoulder repositioning, but the multisensory integration mechanisms with visuo-proprioceptive incongruency. The weighting on vision and proprioception varies depending on the plane/direction of the upper limb movements (Klein et al., 2018). Given that upper limb vision-proprioception integration has been predominantly studied in the two-dimensional horizontal plane using a computer screen (Block & Bastian, 2010; Goodman & Tremblay, 2018; van Beers et al., 2002), it is important to understand multisensory integration mechanisms for movements in different planes (e.g., vertical). Immersive VR is one of the best tools to test the multisensory integration for vertical plane movements by creating visuo-proprioceptive incongruency.

The purpose of the present study was to investigate the effect of visual offset when participants were instructed to ignore vision during a joint repositioning task using a JPS test. It was hypothesized that 1) induced visual offsets would result in repositioning errors consistent with the direction of the visual offset, and 2) the same trend in joint repositioning error would be observed when participants were informed about the visual offset and instructed to ignore vision.

2. Methods

2.1. Participants

Twenty-five individuals without a history of chronic upper extremity pain, injury, and neurological disorder participated in the current study (female/male: 13/12, age: 22.7 ± 5.3 yr, height: 1.7 ± 0.1 m, weight: 71.5 ± 13.6 kg). All participants provided informed consent as approved by the University of Oregon Institutional Review Board.

2.2 Instrumentation

Participants were outfitted with an HTC VIVE VR headset (2160 x 1200 resolution, PenTile OLED display) with headphones attached (HTC VIVE, Xindian District, New Taipei City, Taiwan) (*HTC VIVE Tracker (3.0) Developer Guideline Ver 1.1*, 2021). A wrist brace was fitted to their dominant arm and an HTC VIVE tracker with Velcro tape was attached to the bottom of the tracker. The Velcro tape was enough to secure the tracker on the wrist and control unwanted movement of the tracker due to gravity, as the tracker data was needed only when the participant kept their hand at a certain shoulder elevation angle. Auditory instructions and cueing were delivered through the headphones. A 3D VR environment including a visual representation of the dominant wrist position in the space was displayed to the participant through the headset. Wrist position was projected as a baseball size black ball that matched the wrist tracker position in accurate vision trials. In offset vision trials, this black ball position shifted ± 8º in the vertical axis using the arm length of each participant for this calculation. Wrist position was determined using output from the VIVE tracker, serving as the source of kinematic data for the current study (Spitzley & Karduna, 2019). A small (1 to 2 cm) mismatch towards the medio-lateral direction between the actual wrist position and the virtual hand position existed in both accurate and offset vision trials when participants elevated their arm with palm facing inward, as the virtual hand was centered on the tracker placed on the dorsal wrist.

2.3 Experimental procedure

Participants were seated on a kneeling chair, allowing for a full range of arm motion while keeping their posture upright and minimizing oscillating on a chair during the experiment. A custom VR environment only contained plain white walls and a visual representation of a participant's dominant wrist to eliminate environmental visual references that participants could use to estimate their body or segment position in the VR space. The HTC VIVE tracker was affixed to the wrist while the participant's dominant arm was at their side, with fingers pointing perpendicular to the ground. This allowed for the starting position of the tracker to be as close as possible to 0º rotation in the vertical axis of the tracker. Participants were asked to keep their palm facing inward throughout the experiment.

The participants then performed a JPS test with shoulder flexion movement with the elbow fully extended (Spitzley & Karduna, 2022). One trial of the JPS test consisted of two phases, the presentation phase and the replication phase. In the presentation phase, auditory cues guided participants to a target shoulder flexion angle. A low tone sound was emitted from the headphones when the arm was more than 5º below a target, and a high tone sound was emitted when the arm was more than 5º above a target. No sound was heard when the arm was within a 5º range of a target. The participant kept their arm at a target angle for 3 consecutive seconds, and then moved it back to their side when the audible cue "relax" was emitted. The replication phase started 3 seconds after the end of the presentation phase. No auditory guidance regarding the arm angles was provided during this phase. Participants moved their arm to the remembered target and kept it at the target angle for 3 consecutive seconds until another "relax" cue was emitted. A visual representation of the wrist was displayed throughout the entire JPS trial. Further details of the JPS test paradigm can be found in a previous study from our lab (Spitzley & Karduna, 2022).

Three blocks of 12 JPS trials were performed in the same order across all participants. Within each block, the target angles 85, 90, 95, and 100º were tested in a randomized order. The target angles were varied within a relatively small range in order to avoid learning effect from trial to trial and in the meantime to minimize effect of target angle on repositioning errors. The first block was the familiarization block (FB) where participants were familiarized with the VR environment and the JPS test. The dominant wrist position displayed in the VR environment was always congruent with the actual wrist position in the real-world space throughout this block. The second block was offset block 1 (OB1) where a ±8º visual offset in the vertical axis of the wrist position was introduced in the replication phase for a portion of the 12 trials. Of the 12 trials, 4 were performed with -8º offset, 4 were performed with +8º offset, and 4 were performed with 0º offset (no offset). For example, in -8º offset trials the participant saw their wrist at 82º of shoulder flexion position when they flexed their shoulder to 90º. In the final block called offset block 2 (OB2), the visual offsets were introduced in the same way as OB1. However, before beginning OB2, participants were given the following instructions: "Your vision may or may not be accurate. Ignore vision, instead rely on where you sense your arm is in the space." Two to three minutes of rest was provided between each block to prevent fatigue. Within OB1 and OB2 blocks, the order of visual offset was randomized. Trials were performed three times at each target angle (85, 90, 95, and 100º) while these three trials had all different visual offset angles (-8º, 0, and +8º) (**Figure 2.1**). Proprioception only trials with no information of the wrist position (no vision trials) were not included in the current study, as our previous study found no difference in repositioning errors between accurate vision and no vision in the same JPS test (Spitzley & Karduna, 2022).

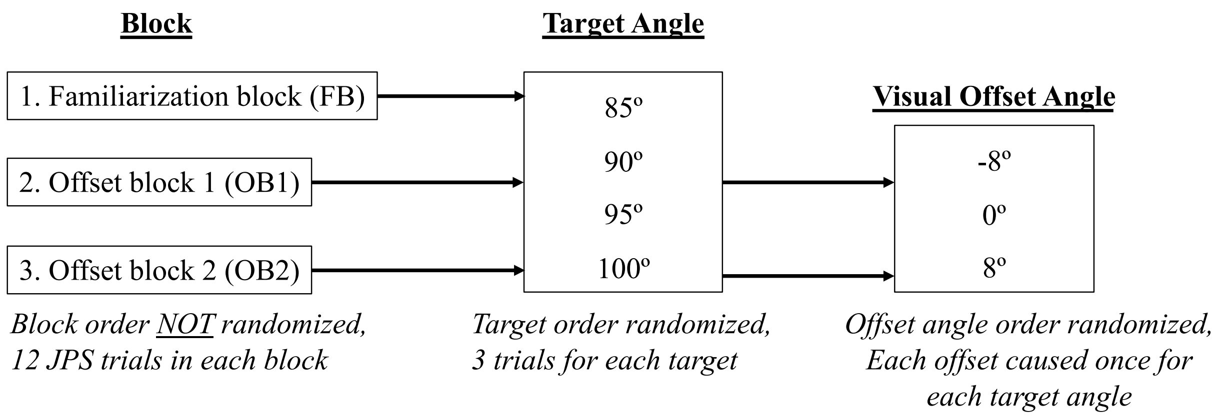


Figure 2.1. Flow of JPS test. All participants started with FB, followed by OB1 and OB2. Within each block, the target angles varied between 85º and 100º with their order randomized. For the offset blocks, each target angle was performed at -8º, 0º, and 8º visual offset.

2.4 Data Extraction

Data were sampled from the VIVE tracker at 90 Hz and collected using a customized Unity program (Unity Technologies, San Francisco, CA). Shoulder flexion angles were calculated with respect to vertical (the 0º starting position of the tracker). Mean shoulder flexion angles in the presentation and replication phases were calculated by averaging 100 data points prior to each "relax" cue.

The following equations were used for each trial (i):

$$Constant\ Error\ (CE) = \theta_m = \left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e) \qquad \textbf{(Eq.2.1)}$$

$$Variable\ Error\ (VE) = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e - \theta_m)^2} \qquad \textbf{(Eq.2.2)}$$

θ_p is the mean presentation angle, θ_r is the mean replication angle, θ_e is the repositioning error $(\theta_r - \theta_p)$, and n is the number of trials performed within a block.

The reliance on visual and proprioceptive information (VP reliance score) during the OB1 and OB2 blocks was estimated using the equation:

$$VP\ reliance\ score = \left(\frac{CE_{OB} - CE_{Last\ 4\ trials\ of\ FB}}{8^{\circ}}\right) \times (-1\ or\ 1) \quad \textbf{(Eq.2.3)}$$

CEs from the last four trials of FB and the corresponding offset block, either OB1 or OB2, were used to get a VP reliance score for each offset block. Depending on the visual offset condition, either -8º or 8º, -1 or 1 was multiplied to make the score fit within the scale of 0 to 1. A score of 1 indicated that participants positioned their arm 8º higher or lower in the offset blocks than FB, depending on the direction of the visual offset, indicating that participants relied on their vision to reposition their arm. A score of 0 indicated that participants repositioned their arm at the same angles in both FB trials and OB trials, indicating participants relied on their proprioceptive information.

2.5. Statistical analyses

An a priori power analysis was conducted using G*Power version 3.1.9.6 (Faul et al., 2009) to determine the minimum sample size required to test the study hypotheses. Results indicated the required sample size to achieve 80% power for detecting a medium effect, at a significance criterion of $\alpha = .05$, was $N = 24$ for two-way repeated measured ANOVA. Thus, the obtained sample size of $N = 25$ is adequate to test the study hypotheses.

Normality of the sample distributions for CE, VE, and VP reliance score were examined by Shapiro-Wilk tests. If the sample distribution was found skewed, the data was log-transformed and forced to be normally distributed. If the sample distribution was not found skewed, outlying samples that fell more than 3 times the interquartile range above the third quartile or below the first quartile were excluded. The effect of block (OB1 and OB2) and visual offset (-8, 0, and +8º) on these variables were then examined using two-way repeated measures ANOVAs. If a significant main effect or interaction was observed, pairwise t-tests with a Bonferroni correction were performed for *post-hoc* testing. For all the statistical tests, the alpha level was set at 0.05. Effect size η^2 was calculated for each of main effects and interactions in ANOVAs. η^2 of 0.01, 0.06, and 0.14 indicate small, medium, and large effect, respectively. All statistical analyses were performed using R 4.2.2 (R Core Team).

3. Results

The sample distribution of CE was not found to be significantly skewed with a Shapiro-Wilk test ($p = 0.38$). One participant was excluded as the data did not fall within the normal range defined using the interquartile range. The means and standard deviations of CEs in OB1 with -8, 0, and +8º visual offsets were 5.5 ± 3.6º, 1.2 ± 1.9º, and -7.5 ± 3.7º, respectively. The means and standard deviations of CEs in OB2 with -8, 0, and +8º visual offsets were 3.3 ± 4.1º, -0.3 ± 2.3º, and -4.3 ± 3.2º, respectively. A two-way repeated measures ANOVA identified a small main effect of block ($p = 0.03$, $\eta^2 = 0.04$) and a large main effect of visual offset ($p < 0.001$, $\eta^2 = 0.40$), while no interaction was found ($p = 0.10$, $\eta^2 = 0.03$). Pair-wise t-tests with Bonferroni correction were performed for post-hoc testing. Statistically significant differences in CE were found between each pair of comparisons between -8º, 0º, and 8º visual offsets (all $p < 0.001$) (**Figure 2.2**).

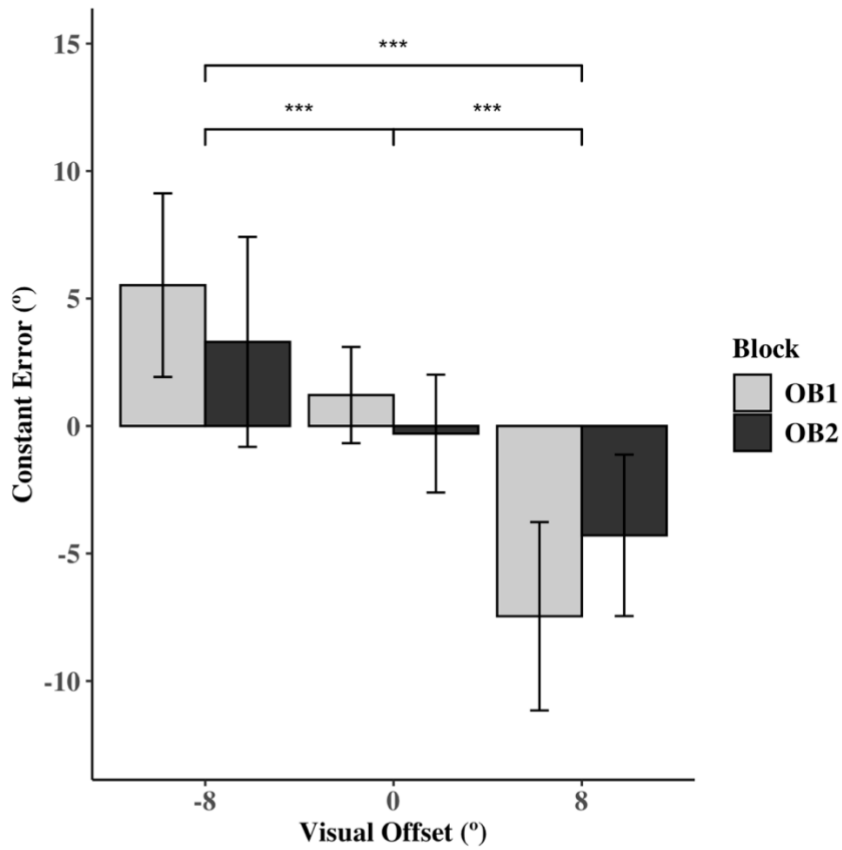


Figure 2.2. CE at each testing block and visual offset condition. OB1 stands for Offset Block 1 during which no instruction regarding visual offset was given. OB2 stands for Offset Block 2 during which participants were instructed to ignore vision. Asterisks on top of the brackets indicate significant differences between visual offsets. The main effect of block was found as well ($p = 0.03$). Each bar paired with an error bar represents the mean and the standard deviation, respectively, in each testing condition. ***: $p < 0.001$

The sample distribution of VE was found to be significantly skewed with a Shapiro-Wilk test ($p < 0.001$), and therefore the data was log-transformed before running an ANOVA. The means and standard deviations of VEs in OB1 with -8, 0, and +8º visual offsets were 1.3 ± 1.1º, 1.4 ± 1.2º, and 1.2 ± 1.2º, respectively. The means and standard deviations of VEs in OB2 with -8, 0, and +8º visual offsets were 1.1 ± 1.1º, 1.1 ± 1.1º, and 1.6 ± 1.6º, respectively. A two-way repeated measures ANOVA identified no significant main effect of block ($p = 0.53$), visual offset ($p = 0.50$), or interaction ($p = 0.59$) (**Figure 2.3**).

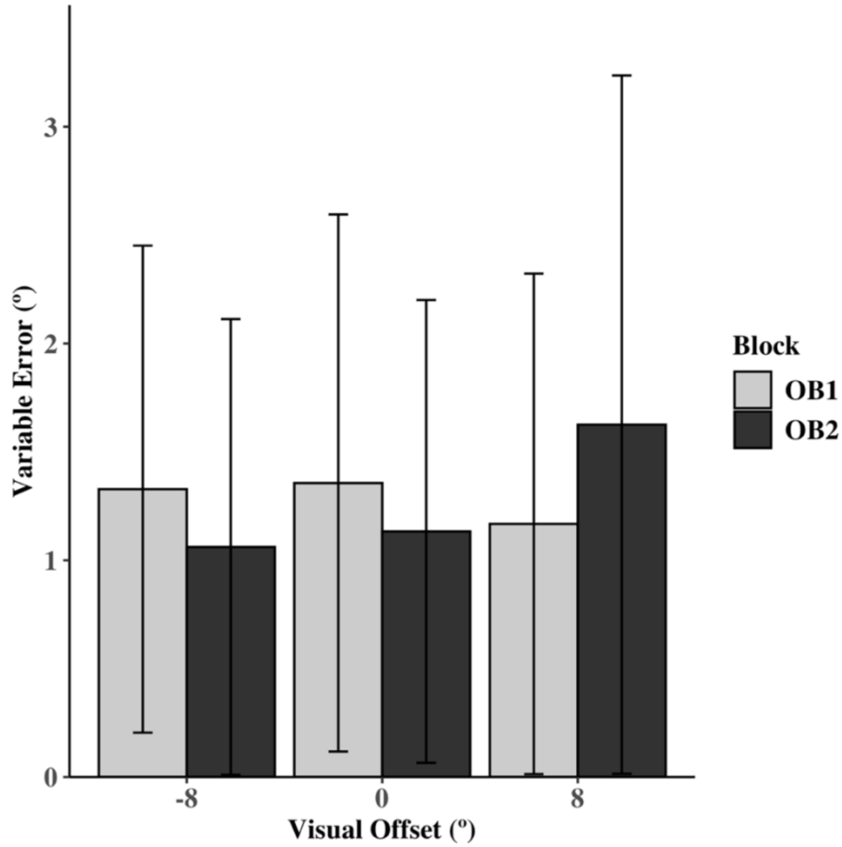


Figure 2.3. VE at each testing block and visual offset condition. Neither a main effect nor interaction was found ($p > 0.05$). Data shown in the figure are the raw data that is not log-transformed. Each bar paired with an error bar represents the mean and the standard deviation, respectively, in each testing condition.

The sample distribution of VP reliance score was not found significantly skewed with a Shapiro-Wilk test ($p = 0.64$). Two subjects were excluded as their data did not fall within the normal range defined using the inter-quartile range. The means and standard deviations of VP reliance score in OB1 with -8 and +8º visual offsets were 0.8 ± 0.4 and 0.8 ± 0.3, respectively. The means and standard deviations of VP reliance score in OB2 with -8 and +8º visual offsets were 0.5 ± 0.4 and 0.4 ± 0.3, respectively. A two-way repeated measures ANOVA identified no significant main effect of block (p = 0.13), visual offset (p = 0.45), or interaction (p = 0.99) (**Figure 2.4**).

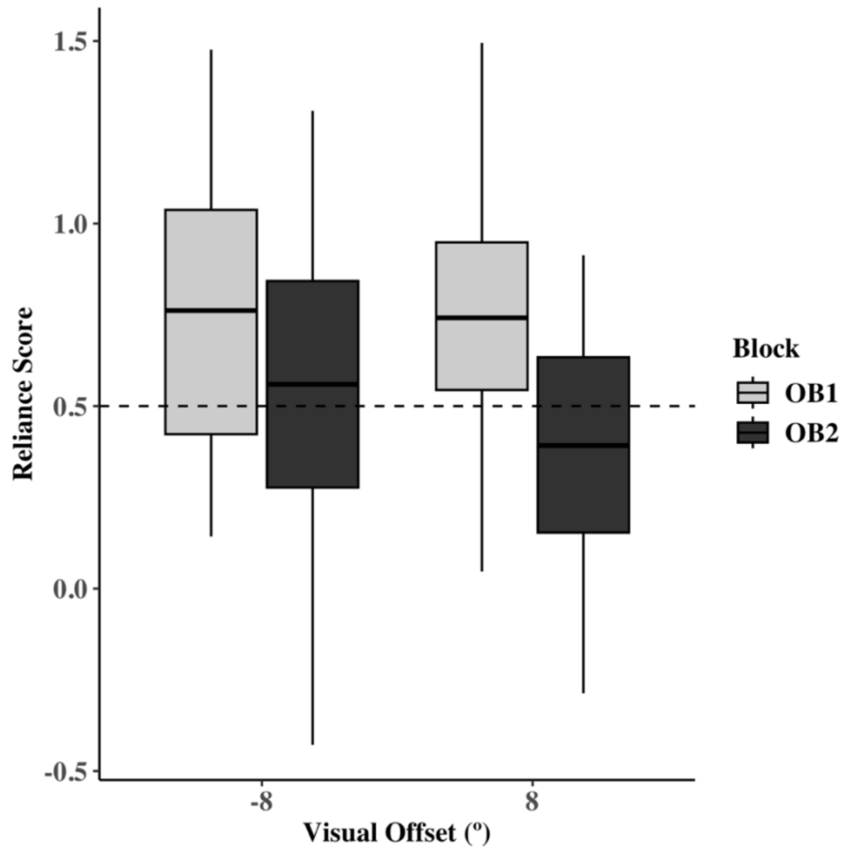


Figure 2.4. VP reliance score at each testing block and visual offset condition. No significant main effect or interaction was found ($p > 0.05$). A horizontal dashed line at VP reliance score of 0.5 indicates the equal distribution of vision and proprioception. The thick horizontal black line in each box represents the median and the box itself represents an inter-quartile range in each testing condition. The vertical line on top and bottom of each box represents max and min values.

4. Discussion

The purpose of the present study was to investigate the effect of visual offset when participants were instructed to ignore vision in a shoulder JPS test. The hypotheses of the current study were: 1) induced visual offsets would result in repositioning errors consistent with the direction of the offset, and 2) the same relationship between visual offset and repositioning error would be observed even when participants were informed about offsets and instructed to ignore vision. The first hypothesis was fully supported by the CE results (**Figure 2.2**). The CEs were significantly larger in the trials with visual offsets (5.5º CE with -8º offset and -7.5º CE with +8º offset) than the trials without a visual offset (1.2º CE with accurate vision). Visual offset trials demonstrated CEs that closely matched the magnitude of the induced offset. This is consistent with results reported in previous work from our lab which demonstrated a -9º CE with a +8º visual offset at a target angle of 90º (Spitzley & Karduna, 2022). Furthermore, the VP reliance score in OB1 was 0.75 on average, which indicates that the participants' perception of the position of their arm were biased towards the visual representation of their hands in VR rather than their actual hands. The second hypothesis was partially supported by the results, as the CEs in the trials with visual offsets (± 8º) in OB2 were significantly smaller compared to OB1 trials (main effect of block), but larger compared to 0º offset (i.e., accurate vision) trials within OB2 itself (main effect of visual offset) (**Figure 2.2**). Awareness of visual offset appears to help reduce the CEs to some extent, but the offset vision still results in errors in repositioning accuracy even though the participants were aware of the offset.

Visual offsets significantly influenced repositioning errors in the current study, and this held true even when the participants were informed about the errors and instructed to ignore vision. This supports previous findings by other sensorimotor studies indicating that vision is a strong sensory input in the human body system and humans integrate vision in their CNS to plan and execute the body movement even if the vision is recognized as faulty (Berger & Bülthoff, 2009; Block & Bastian, 2011b; Hsiao et al., 2022). However, the 40% decrease in CE between OB1 and OB2 demonstrated that relative weighting of vision and proprioception may be adjusted when given the instruction to ignore the faulty visual cue in OB2. These results support the concept that humans can control the relative weighting of vision and proprioception to some extent in the context of upper limb joint repositioning movements. VEs were not different between blocks or visual offsets (**Figure 2.3**). This indicates that the participants were making consistent repositioning errors (CEs) in each trial condition and each block. In the present study, the absence or presence of visual offset was randomized and instruction on how to complete the task changed between blocks. That said, the consistent VEs further strengthen our findings around the effect of visual offset awareness on joint repositioning accuracy. No statistical difference was found in VP score across the blocks or visual offsets, despite a trend toward lower VP in OB2 than OB1, especially in the trials with +8º offset. A decreasing trend in the weighting of vision when instructed to ignore vision, which was apparent in a lower VP score in OB2, is aligned with findings in a previous study that tested the body orientation repositioning involving visual, proprioceptive, and vestibular cues (Berger & Bülthoff, 2009). They reported that, while repositioning accuracy was influenced by visuo-proprioceptive incongruency, participants were able to reduce the magnitude of the influence when informed about the visual offset. Overall, the current study found that humans can up- and down-weight their relative reliance on vision and proprioception, while completely ignoring vision was difficult, possibly due to the dominance of vision during the body movement planning and execution (Bayramova et al., 2021; Valori et al., 2020).

The current study revealed vision as a dominant sensory input over proprioception in a shoulder JPS test. Previous studies have demonstrated that the relative weighting of vision and proprioception varied depending on a variety of conditions (Block & Bastian, 2010, 2011b). We evaluated the accuracy of joint repositioning through shoulder flexion movements, which relied on a previous memory of vision and proprioception. The relative weighting of vision and proprioception could be different depending on the plane of motion. For example, vision is likely to be more heavily weighted in horizontal plane movements (Apker et al., 2011; van Beers et al., 2002). More obvious, easily detectable inaccurate visual cues, such as a greater visual offset angle instead of a ± 8º, could lead to an upweighted use of proprioception. However, a motor learning study found that an easily detectable visual offset with 45º rotated virtual hand movement on the horizontal plane still influenced the reaching hand movement patterns over the reaching trials (Morehead et al., 2017). Population is another factor that may affect the visuo-proprioceptive weighting. One of the examples is subjects with a deafferented nervous system who receive no proprioceptive feedback about their limb movements from moving limbs to the CNS. These people are still capable of making adjustments in their intended movements using vision and efference signals coming from the CNS to a moving limb (Medina et al., 2010; Tsay et al., 2023), but they are more likely to exhibit a lower involvement of proprioception in reaching movements compared to people without deafferentation. From an aging perspective, individuals under 8 and over 45 years show a greater contribution of vision than young adults, potentially because their proprioceptive functions are either under development or in decline (Henry & Baudry, 2019; Rand et al., 2013). VR systems have the potential to be used as rehabilitation/training tools for patients (J. Chen et al., 2022) and trainees in a variety of fields including medical practitioners (Kyaw et al., 2019). The effect of population differences, including physical health condition and age, as well as body movement patterns being tested or learned such as the primary planes of movements and the involvement of multi-joint coordination using a VR system (Klein et al., 2018; Ma et al., 2012) need to be taken into consideration to enhance the effectiveness of VR rehabilitation/training.

A fully immersive VR system provides much more robust and complicated visual field perturbations that traditional visuo-proprioceptive integration studies are not able to investigate. Classically, reaching movements with visual perturbations have been studied in a 3D environment using prism goggles (Hansen et al., 2007) or in a 2D environment using computer screens (Brouwer et al., 2002). These models are very different from what we experience in daily lives in terms of reaching movements. A 3D VR environment, in turn, can create a well-controlled 3D environment that closely replicates the real world while minimizing the undesirable influence of external factors. Reaching with blurry vision (Schroeger et al., 2021) and catching a dynamically moving target (Singh et al., 2020) are examples of what the traditionally available devices were not able to study, but the VR systems can. It is even possible with recently released untethered portable VR headsets to bring a VR system to hospitals or training facilities to test patients or athletes who are not easily accessible for experiments occurring in research laboratories (*Meta Quest 3*, n.d.; *VIVE XR Elite - Convertible, All-in-One XR Headset*, n.d.). The availability of VR systems in research and clinical settings will open up new areas of human body systems that have not been understood in the current literature.

A few limitations of the current study need to be mentioned. JPS is not a suitable protocol for visuo-proprioceptive coordination for those with short-memory deficiency, as the repositioning errors partially depend on the memory of the presenting phase (Edwards et al., 2016). While our self-reported screening on neuromuscular health conditions served to exclude individuals with short-memory deficiency, it might not be effective if a participant is not aware of their health condition. A JPS test with fewer target angles than the current study may be used for this population, so that the effect of short-memory deficiency is alleviated. Although different upper limb reaching paradigm could have been used to avoid the short-term deficiency problem

(Roach et al., 2023), the JPS was selected for this study to confirm our hypotheses. The order of blocks was not randomized in the current study. All participants started with FB followed by OB1 and OB2 as the different instructions that were sensitive to the order needed to be given in each block. Learning effect from a previous block potentially influenced the results in the following block(s) as the participants may have gotten better in the accurate joint repositioning over the course of the three blocks. However, learning effect from a previous trial within each block was considered minimized since we randomized the combinations of a target angle and a visual offset angle, besides their orders within a block.

5. Bridge

The study outlined in this chapter was a follow-up to one of the previous studies from our lab and provided the foundational knowledge about the dominance of vision in a joint repositioning test when physically healthy young individuals including both females and males are tested. It also provides the insights into a possibility that a relative reliance on vision and proprioception can be controllable by conscious effort or could potentially differ between people with different characteristics such as athletes. In the Chapter IV, the same joint repositioning test, an active shoulder JPS test, is performed by collegiate baseball and softball athletes and their respective control group that are matched by sex, age, and throwing arm side.

CHAPTER III

DOMINANCE OF PROPRIOCEPTION OVER VISION IN A NOVEL DYNAMIC REACHING TASK IN VIRTUAL REALITY

This work is currently in preparation for submission to the Journal of Motor Behavior and is co-authored by Motoki Sakurai, Taylor J. Wilson, and Dr. Andrew R. Karduna. The study design, experimental work including data collection and analysis, and writing was performed by Motoki Sakurai. Taylor J. Wilson contributed to study design. Dr. Andrew R. Karduna provided research mentorship and editorial assistance.

1. Introduction

Human motor control during upper limb reaching is a complex process that integrates multiple sensory inputs, primarily vision and proprioception (Apker et al., 2011; Berger & Bülthoff, 2009; Block & Bastian, 2010). Optimal integration theory proposes that the relative reliance on these sensory inputs are context-dependent and weighted optimally to maximize reaching accuracy for a given situation (Ernst & Banks, 2002), with vision typically dominating in "static" reaching tasks, such as reaching for a coffee cup (Goodman & Tremblay, 2018; Spitzley & Karduna, 2022). Although speculative, the relative weighting between vision and proprioception may shift in "dynamic" tasks, where both the reaching target and the hand are moving such as catching a thrown ball. This can potentially increase the reliance on proprioception due to the difficulty of tracking both moving objects simultaneously.

In sports like baseball, accurate dynamic reaching in three-dimensional (3D) space is essential. Traditional reaching paradigms are often confined to two-dimensional (2D) using a handheld manipulandum or computer displays (Fialho & Tresilian, 2017; Tsay et al., 2023). These traditional tests do not enable us to understand the complexities of on-field situations where players reach for moving targets in 3D (Klein et al., 2018). To address this gap, we have developed a novel reaching test to establish a basic understanding of how humans weigh vision and proprioception when they reach for a dynamically moving ball in 3D space using an immersive virtual reality (VR) system.

VR has emerged as a promising tool for studying motor control due to its robust capabilities in manipulating 3D visual fields and collecting valid and reliable kinematic data (Spitzley & Karduna, 2019). Previous studies from our lab have implemented a shoulder joint position sense (JPS) test in a fully immersive 3D VR environment, providing foundational insights into vision-proprioception integration in static reaching tasks (Sakurai et al., 2024; Spitzley & Karduna, 2022). The shoulder JPS test requires subjects to reposition their arm at a previously remembered shoulder elevation angle (Roach et al., 2023). For the current study, results from a shoulder JPS test serves as a baseline for vision-proprioception integration and be compared to a novel dynamic reaching test. Relative weighting of vision and proprioception can be quantified by creating a vision-proprioception mismatch (visual offset), during a reaching test in VR (Spitzley & Karduna, 2022). Visual offset involves projecting a visual representation of the reaching hand in VR at a position that does not match the physical location of the hand (Morehead et al., 2017; Tsay et al., 2023). This approach allows for vision to be dissociated from proprioception, and allows for an assessment of whether the individual is relying more on vision (i.e., visual representation of the hand) or proprioception (i.e., the actual hand) when performing a reaching task.

The purposes of the present study are twofold: (1) create a novel dynamic reaching test with moving reaching targets in fully immersive VR environment, and (2) better understand the relative weighting of vision and proprioception in an on-field dynamic reaching situation and compare it with the JPS. It was hypothesized that visual offset would result in worse reaching accuracy compared to trials without visual offset in both the JPS test and the dynamic reaching test. It was further hypothesized that proprioception would be more heavily weighted relative to vision in the dynamic reaching test compared to the JPS.

2. Methods

2.1. Participants

Twenty-seven (Female/Male: 15/12) physically healthy right-handed individuals without current upper limb pain or injury participated in this study (Age: 24.0 ± 6.5 yr, Height: 1.7 ± 0.1 m, Weight: 72.5 ± 14.8 kg). All participants provided informed consent as approved by the University of Oregon Institutional Review Board.

2.2. Experiment Setup

Participants were outfitted with an HTC VIVE VR headset (2160 x 1200 resolution, PenTile OLED display) with headphones attached (HTC VIVE, Xindian District, New Taipei City, Taiwan). An HTC VIVE tracker (version 3.0) was placed on a wrist brace and a chest band to track dominant wrist and sternum kinematics, respectively. The wrist tracker was placed on the dorsal wrist, and the trunk tracker was placed on the approximate center of the xiphoid process. Auditory instructions and cueing were delivered through the headphones.

A custom 3D VR environment containing a room with plain walls and a visual representation of the participant's dominant hand were displayed to the participant through the headset. Hand position was projected as a baseball size black sphere positioned at the center of the wrist tracker. It served as a visual representation of the participant's hand in VR and the source of kinematic data for analysis. Although not visually projected in VR, the trunk tracker also provided kinematic data. In the dynamic reaching test, a baseball size red sphere was also projected as a reaching target, which moved towards participants at their shoulder height at 3 m/s from 5 meters distance in front without a gravitational effect (no vertical displacement in ball trajectory) or curvature in its trajectory (**Figure 3.1**). In the JPS test, only the empty room and visual hand were seen in VR, and auditory cues guided the participants to perform trials. All computations of target movements and data extraction were performed using C# scripts attached to a customized Unity program (Unity Technologies, San Francisco, CA).

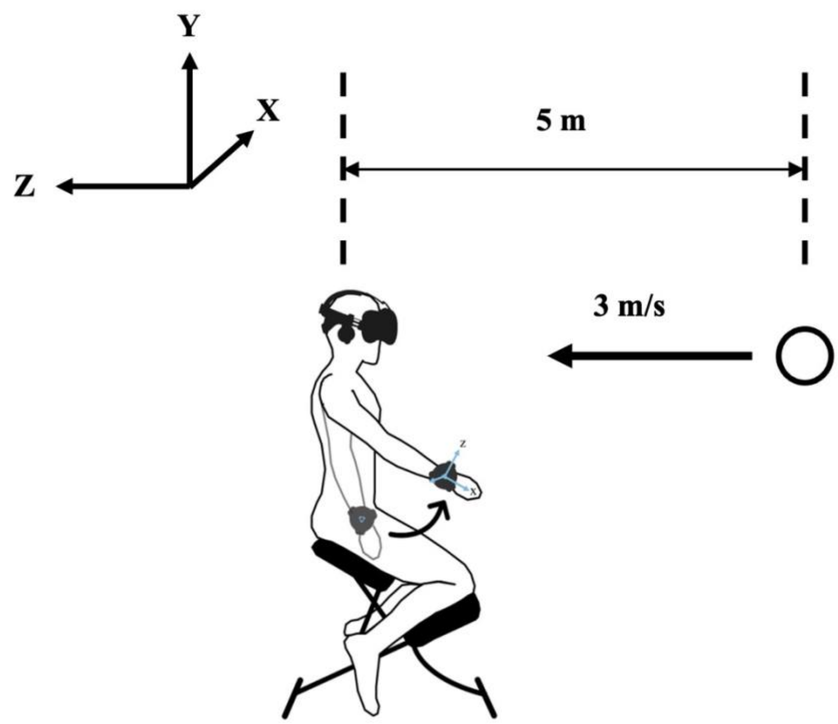


Figure 3.1. Reaching test setup. Participant is seated on a kneeling chair, wearing the headset with over-ear headphones. Trackers affixed to the dominant wrist and the sternum. The reaching target moves from five meters in front of the participant's dominant shoulder at three meters per second.

2.3. Experimental Procedure

For both the dynamic reaching and the JPS test, the participant was seated on a kneeling chair, allowing for full range arm motion while keeping an upright posture and minimizing chair oscillation during the experiments (**Figure 3.1**). The participant always started the trials with their dominant arm relaxed at their side, the palmar side of the hand facing the medial direction, and the elbow fully extended. All shoulder elevation movements performed in both protocols were a single joint shoulder elevation with the elbow fully extended. The participant's arm length from the top of the acromion process to the center of the wrist tracker was measured using a measuring tape, and the dominant shoulder position was measured by placing another HTC

VIVE tracker on top of the acromion process before the experiments began. The order of performing the dynamic reaching test and the JPS test was randomized across participants.

2.3.1. Dynamic reaching test

Both the shoulder position and the arm length data were computed in a customized Unity program to determine reaching target trajectories. While the reaching target's initial position in VR was consistent at 5 meters in front of the dominant shoulder position in all trials, the reaching target trajectories varied between five different endpoints among 0º, ±8º, or ±16º in the horizontal plane (X axis) around the dominant shoulder position between trials (**Figure 3.2A**). The 0º endpoint was in front of the dominant shoulder position, and reaching towards it would result in pure shoulder flexion. Endpoints were defined as the interception point where the participant's hand (wrist tracker center) would contact the ball if the participant moved their hand to the reaching target at the correct timing.(Su et al., 2014) However, the reaching target became invisible 0.1 seconds before the hand reached the target endpoints in order to prevent providing the participant knowledge about their reaching accuracy in each trial. Hiding the target right before the hand-target contact enabled us to test the reaching accuracy over trials while limiting learning effect from previous trials.

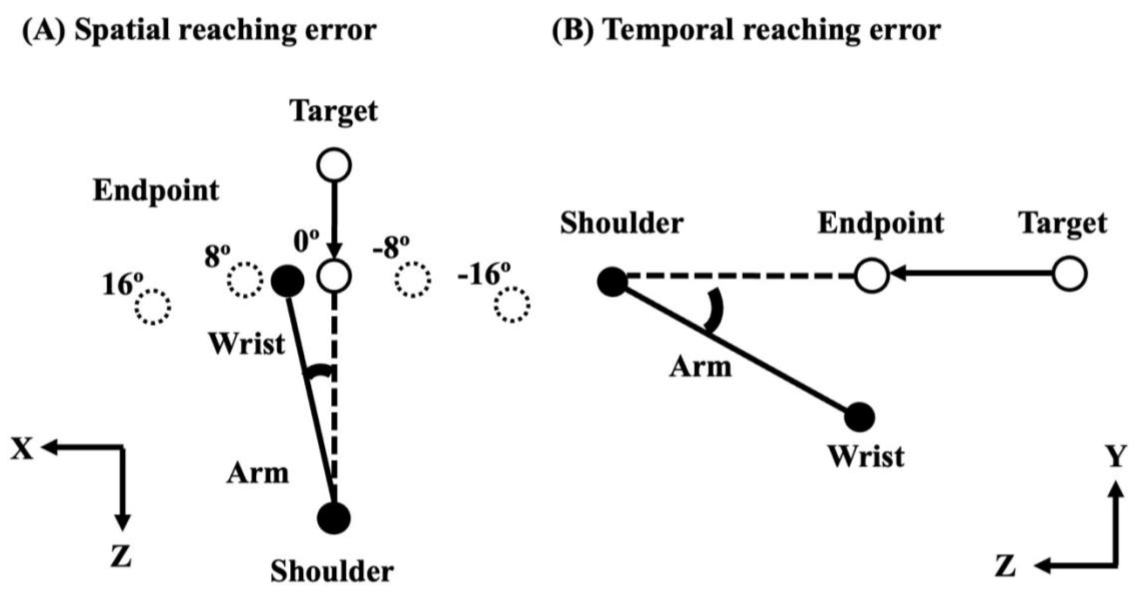


Figure 3.2. Schematic 2D view of the dynamic reaching test setup in VR environment with left-handed coordinate system. (A) Superior view of spatial reaching error. Target moved along the Z axis and reached to one of the five endpoints varied in horizontal plane (X axis). (B) Lateral view of temporal reaching error. Target moved at the participant's shoulder height, and the participant needed to elevate the arm to shoulder height at the correct timing to hit the target.

The dynamic reaching test consisted of 30 trials in each of three blocks: accurate vision block (AB_D), no vision block (NB_D), and offset vision block (OB_D). Within each block, the first 20 trials were adaptation trials, and the last 10 trials were post-adaptation trials. Visual conditions differed between the blocks only in the adaptation trials, while the post-adaptation trials in each block were all performed with no visual information about the reaching hand position in VR (**Figure 3.3**). In AB_D, the dominant hand position displayed in the VR environment was always congruent with the actual hand position in the real-world space. In NB_D, no visual information about the hand position was provided. In OB_D, the hand position was offset by 8º to the left with the participant's arm length taken into account. The task involved slicing through the moving target with a smooth continuous shoulder elevation movement. The participant was not allowed to place their hand at the target endpoint early and wait till the ball reaches to the endpoint. This way, the participant needed to elevate their shoulder to the correct position at the correct timing in order to accurately hit the target. Both target endpoints and block order were randomized across participants.

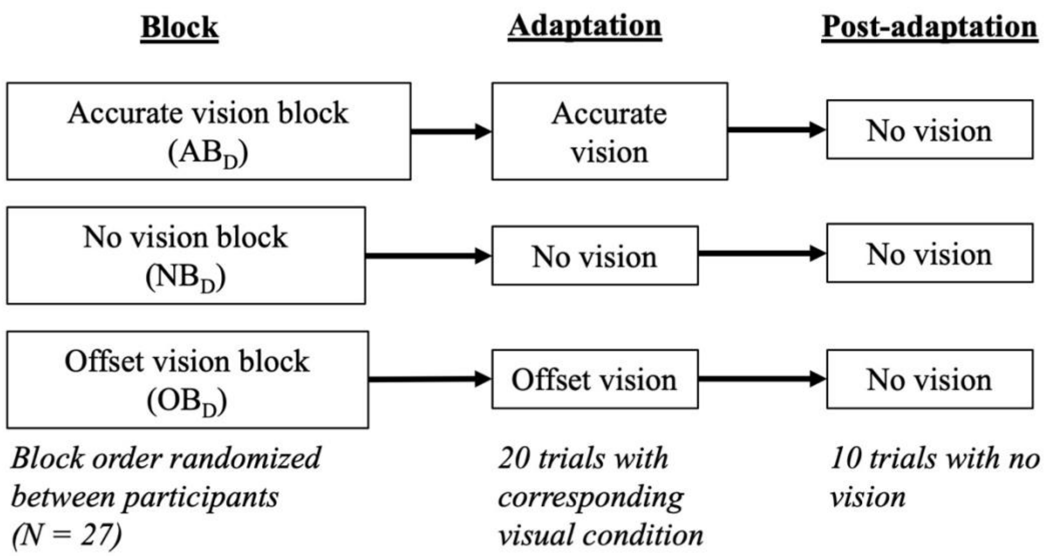


Figure 3.3. Flow of the dynamic reaching test. Visual representation of the reaching hand was projected at the accurate position in AB_D, was not projected in NB_D, or was projected at the inaccurate position by 8º in OB_D during adaptation trials. In post-adaptation trials, the virtual hand position was not projected consistently regardless of what block the participant was performing.

2.3.2. JPS test

Complete details of the JPS test setup in VR can be found in a previous study from our lab.(Spitzley & Karduna, 2022) The shoulder JPS test consisted of 10 trials in each of the two blocks: AB_J and OB_J. Each trial during the JPS test consisted of two phases: presentation phase and replication phase. Within each block, shoulder flexion target angles at 80º, 85º, 90º, 95º, and 100º were tested twice in a randomized order. In the AB_J, the dominant hand position displayed in the VR environment was always congruent with the actual hand position in the real-world space in both the presentation and replication phase. In the OB_J, the participant saw their hand at

8º above their actual hand position in the replication phase. Therefore, participants performed the presentation phase with congruent vision and proprioception, while vision was dissociated from proprioception in the replication phase. Proprioception only trials with no information of the hand position (NB_J) were not included in the current study, as our previous study found no difference in repositioning errors between accurate vision and no vision in the same shoulder JPS test (Spitzley & Karduna, 2022).

2.4. Data Extraction

Kinematic data were sampled from the VIVE trackers at 90 Hz and collected using a customized Unity program both during the dynamic reaching test and the JPS test. In the dynamic reaching test, the constant spatial error (CSE) and the constant temporal error (CTE) were calculated using the **Eq.3.1**.(King et al., 2013)

$$Constant\ Spatial\ Error\ (CSE) = \theta_m = \left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e) \quad \textbf{(Eq.3.1)}$$

The spatial reaching error, θ_e, was the difference between the wrist tracker position and the target endpoint in degrees. (n) is the number of trials performed within a block and (i) is each trial. CSE defines the mean spatial reaching errors over the trials with directions, either positive or negative with respect to the target endpoint in the X axis (mediolateral) (**Figure 3.2A**) (Morehead et al., 2017; Schroeger et al., 2021). CTE were calculated using the **Eq.3.1** while the θ_e was the time difference in seconds between a timepoint when the wrist tracker reached the target height in Y axis (vertical) and a timepoint when the target reached its endpoint. Calculation processes for absolute spatial and temporal errors (ASE and ATE) as well as variable spatial and temporal errors (VSE and VTE) are provided in the supplemental material. All reaching errors were calculated only for the post-adaptation trials, where all trials were performed with no vision regardless of the block condition (**Figure 3.3**).

Vision-proprioception reliance score (VPRS) in the dynamic reaching test was estimated using **Eq.3.2** (Spitzley & Karduna, 2022).

$$Vision - Proprioception\ Reliance\ Score\ (VPRS) = -\left(\frac{CSE_{OB\mathrm{D}} - CSE_{AB\mathrm{D}}}{8^{\circ}}\right) \quad \textbf{(Eq.3.2)}$$

VPRS quantifies the participant's sensory reliance in the zero to one scale. In **Eq.3.2**, CSE_{OBD} is CSE in OB_D, CSE_{ABD} is CSE in AB_D in the dynamic reaching test. A score of 1 indicated that participants placed their arm 8º towards the negative direction in X axis (to the right) in OB_D than AB_D, indicating that participants only used vision as 8º visual offset was seen in OB_D. A score of 0 indicated that participants placed their arm at the same position in X axis in both AB_D and OB_D, indicating participants only used proprioception.

In the JPS test, shoulder flexion angles were calculated with respect to vertical (the 0º starting position of the tracker). Mean shoulder flexion angles in the presentation and replication phases were calculated by averaging 100 data points prior to each "relax" cue. Constant error (CE) was calculated using the **Eq.3.1** with θ_e being the repositioning error between the mean replication angle and the mean presentation angle for each trial (i). VPRS for the JPS test was calculated using CEs in OB_J and AB_J. Calculation processes for absolute error (AE) and variable error (VE) in the JPS test are provided in the supplemental material.

2.5. Statistical Analyses

An a priori power analysis using G*Power version 3.1.9.6(Faul et al., 2009) indicated the required sample size to achieve 80% power for detecting a medium effect, at a significance criterion of $\alpha = .05$, was $N = 25$ for two-way repeated measures ANOVA. The obtained sample size of $N = 27$ was adequate to test the study hypotheses.

For all reaching and repositioning errors, the data distribution was checked by Shapiro-Wilk tests for normality. Log-transformations were performed to force the skewed data to normally distribute. Following the Shapiro-Wilk test and log transformation, outlying participants data were removed using the inter-quartile range as needed. Paired t-tests were performed for the JPS repositioning errors to compare the differences between AB and OB. Two-way repeated measures ANOVAs were performed for the dynamic reaching errors only in the post-adaptation trials to examine main effect of block (AB_D, NB_D, and OB_D) and endpoints (0, ±8, and ±16º), and an interaction effect. Post-hoc pair-wise t-tests with Bonferroni correction were performed if the reaching errors were found statistically different between the conditions. VPRS between the JPS test and the dynamic reaching test were compared using a paired t-test.

Additionally, the first and last adaptation trial in each block were compared to examine whether the spatial and temporal reaching errors were changed over the twenty adaptation trials. A two-way repeated measures ANOVA, following a Shapiro-Wilk test and a log-transformation if needed, was performed. Post-hoc pairwise t-tests were performed if significant main effect or interaction of blocks and trial numbers were found.

For all the statistical tests, the alpha level was set at 0.05. Cohen's *d* effect size was calculated for paired t-tests. Cohen's *d* of 0.2, 0.5, and 0.8 indicate small, medium, and large effect, respectively (Cohen, 1992). Effect size η^2 was calculated for each of main effects and interactions in ANOVAs. η^2 of 0.01, 0.06, and 0.14 indicate small, medium, and large effect, respectively (Adams & Conway, 2014). All statistical analyses were performed using R 4.2.2 (R Core Team).

3. Results

Descriptive statistics including the means and the standard deviations for CSE and CTE in the dynamic reaching test and CE in the JPS test are provided in **Table 3.1**. Results for sample distributions and outlying subjects with Shapiro-Wilk test, log-transformation, and inter-quartile range for all variables of interest are provided in the supplemental materials.

Table 3.1. Descriptive statistics of repositioning and reaching errors in the dynamic reaching test and the JPS test. Data are shown in mean ± standard deviation. *P*-values and effect sizes in the dynamic reaching errors are for main effect of blocks. Main effect of target endpoints and interactions between blocks and endpoints are not shown in this table.

Test type	**Variable**	**Accurate vision block (AB)**	**No vision block (NB)**	**Offset vision block (OB)**	***p*-value**	**Effect size**
Dynamic reaching	Constant spatial error (CSE) (degrees)	2.3 ± 6.7	2.1 ± 6.9	-1.0 ± 5.9	< 0.001	$\eta^2 = 0.43$
	Constant temporal error (CTE) (seconds)	-0.1 ± 0.2	0.2 ± 0.1	-0.2 ± 0.2	0.12	$\eta^2 = 0.09$
JPS	Constant error (CE) (degrees)	-0.8 ± 1.5	N/A	-8.9 ± 2.6	< 0.001	$d = 3.7$

3.1. Reaching errors in adaptation trials

To confirm whether adaptation to a given visual condition occurred during the 20 adaptation trials prior to post-adaptation in each block, changes in the spatial and temporal reaching errors from the first to the last trials were examined (**Figure 3.4**). No subject was found outlying for spatial reaching errors in adaptation trials. With 27 participants, the means and standard deviations for spatial reaching errors were -0.1 ± 5.5º in AB_D, 0.2 ± 6.9º in NB_D, and -2.9 ± 6.1º in OB_D (**Figure 3.4A**). A two-way repeated measures ANOVA for spatial reaching errors identified a large main effect of block ($p = 0.003$, $\eta^2 = 0.19$) and a medium effect of interaction between block and trial number ($p = 0.04$, $\eta^2 = 0.11$) without a significant main effect of trial number ($p = 0.75$, $\eta^2 < 0.001$). Post-hoc pair-wise t-tests found that spatial errors were more negative and far from zero (worse reaching accuracy) in OB_D than AB_D and NB_D at the twentieth adaptation trial ($p = 0.001$ and $p = 0.003$, respectively). OB_D also had more negative spatial error in the twentieth trial compared to the first trial ($p = 0.04$), whereas no change was found within AB_D and NB_D ($p > 0.05$).

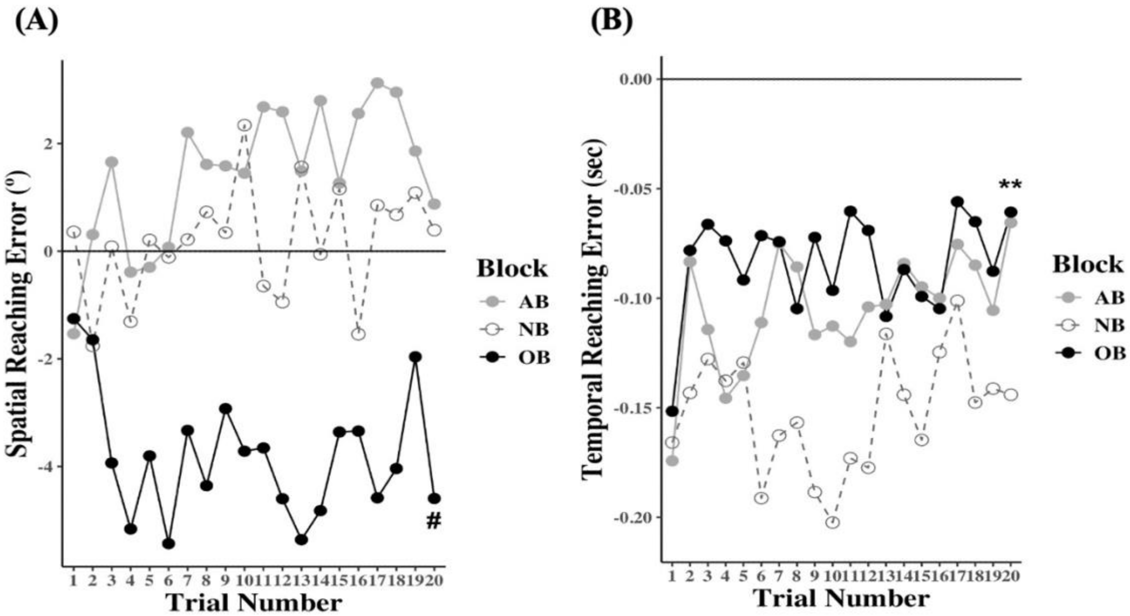


Figure 3.4. Changes in the mean reaching errors over 20 adaptation trials. A horizontal line at zero on Y axes for both figures denote perfectly accurate reaching. The further from zero, the worse the reaching accuracy. (A) Spatial reaching errors in OBD were more negative than ABD and NBD at the twentieth adaptation trials (p = 0.001 and p = 0.003, respectively). The twentieth adaptation trial also had more negative reaching error than the first adaptation trial within OBD itself (p = 0.04). (B) Temporal reaching errors got gradually closer to zero over the 20 adaptation trials (p = 0.002), while no significant block difference was found both at the first and twentieth adaptation trials (p > 0.05).

Two subjects were found outlying for temporal reaching errors in adaptation trials. Thus, 25 participants remained, where the means and standard deviations of the 20 trials for temporal reaching errors were -0.1 ± 0.2s in AB_D, -0.1 ± 0.2s in NB_D, and -0.1 ± 0.2s in OB_D (**Figure 3.4B**). A two-way repeated measures ANOVA for temporal errors in adaptation trials identified a medium main effect of block ($p = 0.04$, $\eta^2 = 0.12$) and a large main effect of trial number ($p = 0.004$, $\eta^2 = 0.28$), while no significant interaction was found ($p = 0.42$, $\eta^2 = 0.03$). Post-hoc pair-wise t-tests, however, found no significant difference between the blocks (all $p > 0.05$). The temporal error was less negative and closer to zero (better reaching accuracy) in the twentieth trial than the first trial ($p = 0.002$).

3.2. Reaching errors in post-adaptation trials with comparison to JPS test

Four subjects were found outlying for CSE. Thus, 23 participants remained, where the means and standard deviations for CSE were 2.3 ± 6.7º in AB_D, 2.1 ± 6.9º in NB_D, and -1.0 ± 5.9º in OB_D. A two-way repeated measures ANOVA for CSE identified large main effects of block ($p < 0.001$, $\eta^2 = 0.43$) and endpoint ($p < 0.001$, $\eta^2 = 0.80$), but no significant interaction ($p = 0.25$, $\eta^2 = 0.05$) (**Figure 3.5A**). Post-hoc pair-wise t-tests found significantly smaller CSE in OB_D than both AB_D and NB_D ($p < 0.001$). Significantly different CSE were also found in each pairwise comparison of all the five endpoints (all $p < 0.05$), except when comparing -16º and -8º ($p = 0.65$).

Three subjects were found outlying for CTE. Thus, 24 participants remained, where the means and standard deviations for CTE were -0.1 ± 0.2s in AB_D, -0.2 ± 0.1s in NB_D, and -0.2 ± 0.2s in OB_D. A two-way repeated measures ANOVA for CTE did not identify any significant main effect of block ($p = 0.07$, $\eta^2 = 0.11$), endpoint ($p = 0.81$, $\eta^2 = 0.02$), or interaction ($p = 0.43$, $\eta^2 = 0.04$) (**Figure 3.5B**).

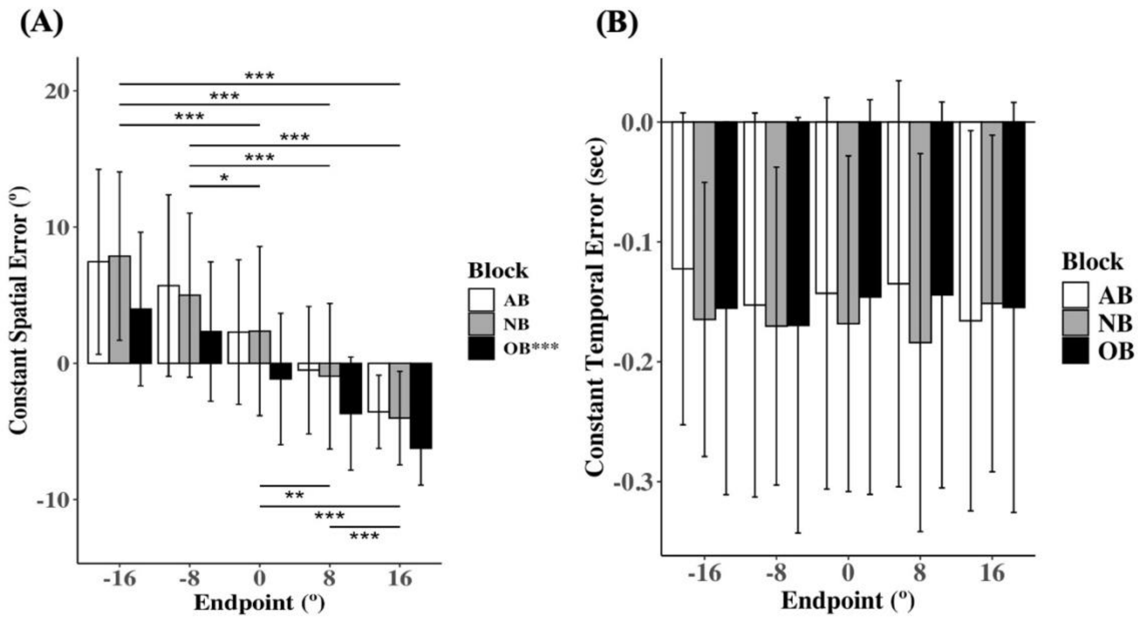


Figure 3.5. Mean constant spatial and temporal reaching errors across participants in the dynamic reaching test. (A) Constant spatial errors (CSEs) were different between the blocks ($p < 0.001$) and the endpoints ($p < 0.001$). (B) Constant temporal errors (CTEs) were not different between the blocks and the endpoints ($p > 0.05$). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Four subjects were found outlying for CE. Thus, 23 participants remained, where the means and standard deviations for CE were -0.8 ± 1.5º in AB_J and -8.9 ± 2.6º in OB_J. A paired sample t-test for CE identified a large effect of block, with OB_J having a significantly smaller CE than AB_J ($p < 0.001$, $d = 3.7$) (**Figure 3.6A**).

Four subjects were found outlying for VPRS in the dynamic reaching test and the JPS test combined. Thus, 23 participants remained, where the means and standard deviations for VPRS were 0.4 ± 0.4 in the dynamic reaching test and 1.0 ± 0.3 in the JPS test. A paired t-test identified that the VPRS in the JPS was significantly higher than the dynamic reaching with a large effect ($p < 0.001$, $d = 1.9$) (**Figure 3.6B**).

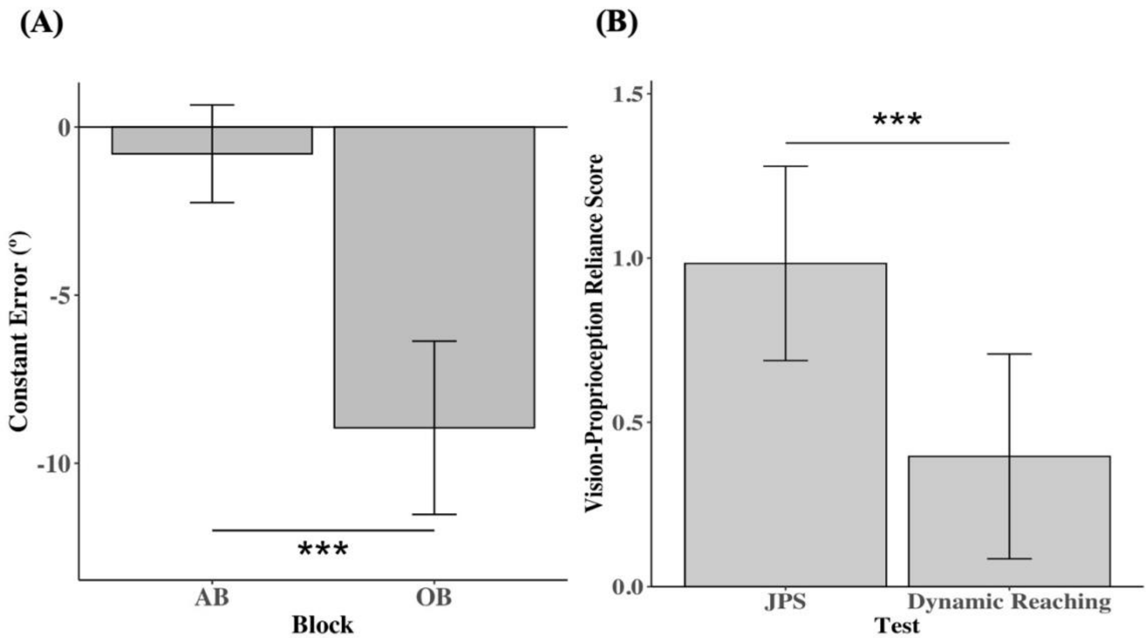


Figure 3.6. (A) Joint position sense test (JPS) results. Constant error (CE) was smaller in offset vision block (OB_J) than accurate vision block (AB_J). (B) Vision-proprioception reliance score (VPRS) was larger in the JPS than the dynamic reaching test. *** $p < 0.001$

4. Discussion

In the current study, it was hypothesized that visual offset would result in worse reaching accuracy compared to trials without visual offset in both the JPS and the dynamic reaching test. Our secondary hypothesis was that proprioception would be more heavily weighted relative to vision in the dynamic reaching test compared to the JPS. The first hypothesis was partially supported by our results, as CSE was worse (far from zero degree) in OB_D than AB_D and NB_D when reaching for the left side endpoints (+8º and +16º). The second hypothesis was fully supported, as the VPRS was smaller in the dynamic reaching than the JPS test. This confirms that proprioception was relied on more in the dynamic reaching compared to that of the JPS test. This is the first study to replicate the on-field reaching situations required in ball sports such as baseball.

No difference in CSE was found between AB_D and NB_D, which aligns with previous findings from our lab using the same JPS protocol (Spitzley & Karduna, 2022). Proprioception only seems sufficient to perform arm reaching movements as accurately when both vision and proprioception are available. However, CSEs showed different trends when vision of the hand position was not accurate in OB. CSEs in OB_D were closer to zero than in AB_D and NB_D when reaching for the left and the middle endpoints (+16º, +8º, and 0º) but more negative when reaching for the right endpoints (-16º and -8º) (**Figure 3.5A**). This indicates that the participant's hand was placed more to their right in OB_D consistently across the endpoints compared to AB_D and NB_D (**Figure 3.2A** for coordinate system reference). As the visual hand position shifted to the left in OB_D, they placed their hand more to the right in an effort to make contact with the reaching target. The visual influence trend was found in JPS tests as well, where participants significantly undershot the target angles in OB_J compared to AB_J (**Figure 3.6A**).

The VPRS provides insights into the influence of offset vision between the dynamic reaching test and the JPS test. In the dynamic reaching test, the VPRS was 0.4 and is significantly smaller than the JPS test and below the halfway point (**Figure 3.6B**). This indicates that although visual offset influenced the CSEs, participants relied slightly more on proprioception than vision in the dynamic reaching, as opposed to the JPS test. It has been commonly found in previous studies and our JPS test results that vision is a dominant sense over proprioception when reaching for static targets (Goodman & Tremblay, 2018; Morehead et al., 2017; Spitzley & Karduna, 2022). However, this was not true when reaching for dynamic targets. Proprioception may have taken over the main role in tracking the hand position in the dynamic reaching test as vision had to keep tracking the moving target. Future studies should integrate eye tracking data into dynamic reaching tests to confirm this hypothesis. In addition, JPS test requires to reposition the arm to a previously remembered target that was once reached by the same arm and is heavily memory based. The dynamic reaching test, however, requires to make a contact between the arm and an external object, in which the reaching target is not a previously remembered position. Such differences between the two tests may have also contributed to the difference in the relative reliance on vision and proprioception as well.

CTE did not statistically differ among blocks and endpoints, which indicates that the manipulations in the visual hand conditions do not influence the ability to time the hand-ball contact in the dynamic reaching test. Previous studies reported that temporal errors were worse when a reaching target ball moved faster or was visually occluded for a longer time duration (Brouwer et al., 2005; Schroeger et al., 2021; Su et al., 2014; Wang et al., 2011). Visual manipulations in the reaching target rather than the visual hand appears to increase the temporal reaching error more. If so, that supports our speculation described above that vision is mainly used to track the target, not the hand. Future studies are encouraged to include different conditions of the reaching target and the visual hand in dynamic reaching protocols.

The novel dynamic reaching test in the current study replicates on-field reaching modalities that ball sport athletes perform during games and can be applied in many ways. These athletes may have better reaching accuracy in this test compared to non-athletic population (Nodehi-Moghadam et al., 2013). The dynamic reaching test can also be used as a rehabilitation tool for patients with limited upper limb range of motion. Previous studies showed that rehabilitation exercises involving dynamic reaching for moving targets increased functional range of motion for patients recovering from stroke (Wang et al., 2011). Future research is encouraged to expand the use of VR technology in a variety of situations.

The current study is not without limitations. An HTC VIVE tracker on the wrist was secured with Velcro tape on a wrist brace. The tracker might have been dragged by gravity and inertia when the participants elevated their arm for reaching, and its dragging was inconsistent when velocities of elevation movement were different. Point of interception where the hand was supposed to hit the target was estimated by computing the participant's arm length and the shoulder position. Although trunk sway was no larger than 0.1 meters in all trials and the elbow was fully extended, the point of interceptions could fluctuate by unconstrained body movements. This ultimately could have affected the accuracy of our spatial and temporal reaching error calculations.

In conclusion, the current novel dynamic reaching task replicated on-field reaching situations in an immersive 3D VR environment. It quantified the spatial and the temporal reaching errors, and the spatial errors were influenced by the visual manipulation in the visual hand positions. However, the extent to which visual manipulation influenced reaching movements were smaller compared to a static reaching task, the JPS test. Proprioception was a dominant sense over vision to track the hand position during reaching. Further studies are warranted to expand the use of VR in motor control skill assessment in a variety of settings such as athletic talent screening and patient rehabilitation.

5. Bridges

The study outlined in this chapter explored whether a novel dynamic reaching task, mimicking the on-field ball catching situation in baseball and softball, provide useful insight into relative reliance on vision and proprioception in a sport-specific situation. Both spatial and temporal reaching error were able to be measured and it was found that vision was down-weighted compared to the static reaching test (JPS test).

In Chapter V and VI, this dynamic reaching test is performed by baseball and softball athletes and male and female non-athletes. Chapter V focuses on the difference between athletes and non-athletes, while Chapter VI focuses on the sex difference in ball catching accuracy as well as temporal arm movement performance.

6. Supplemental materials

6.1. Methods

$$Absolute\ Spatial\ Error\ (ASE) = \left(\frac{1}{n}\right)\sum_{i=1}^{n}(|\theta_e|) \quad \textbf{(Eq. 3.3)}$$

Absolute spatial error (ASE) was calculated in the same way as CSE, except θ_e (spatial reaching error in each trial) was converted to absolute value for each trial. ASE defines the magnitude of the mean repositioning errors over the trials without taking the directions of errors into account.

$$Variable\ Spatial\ Error\ (VSE) = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e - \theta_m)^2} \quad \textbf{(Eq. 3.4)}$$

θ_m is CSE calculated using **Eq.3.1**, and VSE defines the consistency of the magnitudes of the repositioning errors around the target angles, rather than the accuracy of the repositioning.

6.2. Results

Descriptive statistics including the means and the standard deviations for each type of reaching errors in the dynamic reaching test and repositioning errors in the JPS test and are provided in **Table 3.2**.

Table 3.2. Descriptive statistics of repositioning and reaching errors in dynamic reaching test and the JPS test, respectively. Data are shown in mean ± standard deviation. *P*-values and effect sizes in the dynamic reaching errors are for main effect of blocks. Main effect of target endpoints and interactions between blocks and endpoints are not shown in this table.

Test type	Variable	Accurate vision block (AB)	No vision block (NB)	Offset vision block (OB)	*p*-value	Effect size
Dynamic reaching	Absolute spatial error (ASE) (degrees)	5.9 ± 4.0	5.9 ± 4.3	5.5 ± 3.0	0.79	$\eta^2 < 0.001$
	Variable spatial error (VSE) (degrees)	0.6 ± 0.6	0.5 ± 0.5	0.5 ± 0.5	0.85	$\eta^2 < 0.001$
	Absolute temporal error (ATE) (seconds)	0.2 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	0.03	$\eta^2 = 0.13$
	Variable temporal error (VTE) (seconds)	0.02 ± 0.02	0.02 ± 0.02	0.02 ± 0.02	0.52	$\eta^2 = 0.03$
JPS	Absolute error (AE) (degrees)	2.6 ± 1.5	N/A	8.8 ± 2.6	< 0.001	$d = 2.9$
	Variable error (VE) (degrees)	0.5 ± 0.8	N/A	1.6 ± 0.9	< 0.001	$d = 2.4$

6.2.1. Dynamic reaching test

6.2.1.1 Reaching errors in adaptation trials

The sample distributions of the spatial errors were not skewed in AB_D and NB_D ($p = 0.39$ and 0.14, respectively) with Shapiro-Wilk tests, while OB_D was significantly skewed ($p = 0.02$). A log transformation corrected a skewness in the OB_D data, but made AB_D and NB_D skewed (both $p < 0.001$). The raw data without log transformation were used for further analysis that had no outlying participants (N = 27).

The sample distributions of the temporal errors were significantly skewed in AB_D and OB_D ($p < 0.001$ and $p = 0.003$, respectively) with Shapiro-Wilk tests, but not in NB_D ($p = 0.23$). The entire temporal error dataset was therefore log-transformed, and two outlying participants were excluded after the log-transformation (N = 25).

6.2.1.2. Reaching errors in post-adaptation trials

The sample distributions of CSEs in all the three blocks were significantly skewed with Shapiro-Wilk tests ($p = 0.003$, 0.01, and 0.008 for AB_D, NB_D, and OB_D, respectively). The entire CSE dataset was therefore log-transformed, and four outlying participants were excluded after the log-transformation (N = 23).

The sample distributions of ASEs in all the three blocks were significantly skewed with Shapiro-Wilk tests (all $p < 0.001$). The entire ASE dataset was therefore log-transformed to correct the sample distributions. Three participants were excluded after this log-transformation as the data did not fall within the interquartile range (N = 24). The mean and standard deviations for ASE were 5.9 ± 4.0º in AB_D, 5.9 ± 4.3º in NB_D, and 5.5 ± 3.0º in OB_D. A two-way repeated measures ANOVA identified a medium main effect of endpoint ($p = 0.03$, $\eta^2 = 0.11$) and a large effect of interaction between block and endpoint ($p < 0.001$, $\eta^2 = 0.22$) without a significant main effect of block ($p = 0.79$, $\eta^2 < 0.001$). Pair-wise t-tests with Bonferroni correction were performed for post-hoc testing. Significant differences in ASE were found between AB_D and OB_D at -16º, 8º, and 16º endpoints ($p = 0.005$, $p = 0.01$, and $p < 0.001$, respectively), as well as between NB_D and OB_D at 8º and 16º endpoints ($p = 0.02$, and $p = 0.005$) (**Figure 3.7A**). AB_D had a larger ASE than OB_D at the -16º endpoint, whereas OB_D had larger ASEs than AB_D and NB_D at the 8º and 16º endpoints (**Figure 3.7A**). Within-block pair-wise comparisons found significantly larger ASEs in -16º than 8º and 16º endpoints as well as in -8º than 16º endpoints within AB_D ($p = 0.002$, $p < 0.001$, and $p = 0.02$), respectively (**Figure 3.7B**). Within NB_D, ASE was also significantly larger in -16º than 0º, 8º, and 16º endpoints ($p = 0.04$, $p = 0.02$, and $p = 0.03$, respectively) (**Figure 3.7B**).

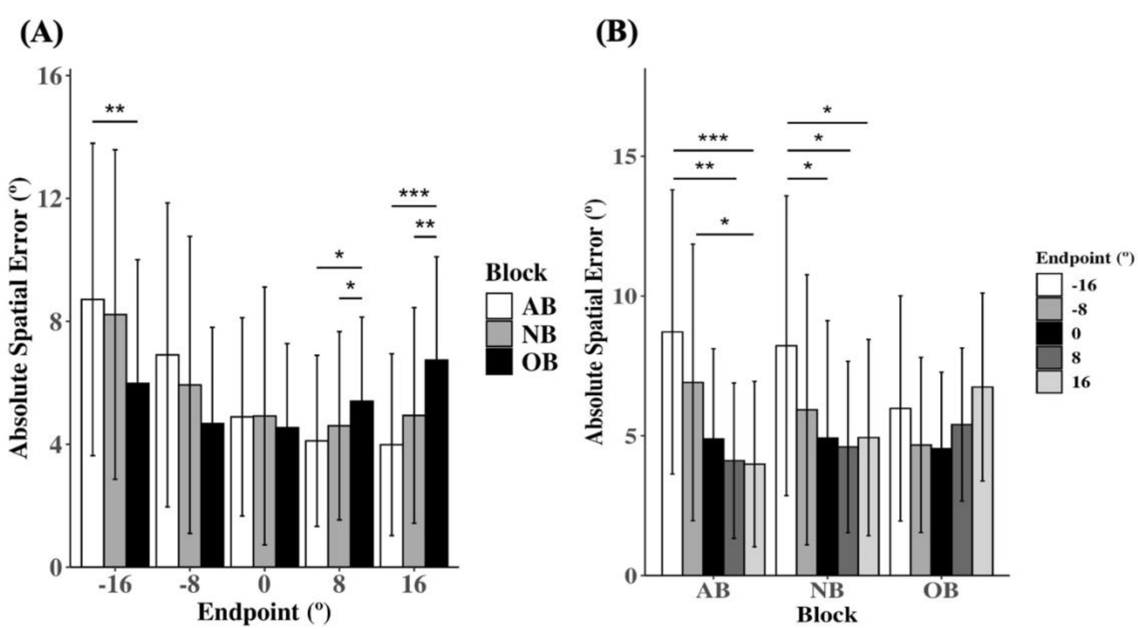


Figure 3.7. Absolute spatial errors (ASEs) had an interaction effect between the blocks and the endpoints. In order to visualize the interaction effect, ASEs are shown (A) as a function of the endpoints and (B) as a function of the block.

The sample distributions of VSEs in all the three blocks were found to be significantly skewed with Shapiro-Wilk tests (all $p > 0.05$). The entire VSE dataset was therefore log-transformed to correct the sample distributions. No outlying subject was found using the interquartile range after the log transformation was performed (N = 27). The mean and standard deviations for VSE were 0.6 ± 0.6º in AB_D, 0.5 ± 0.5º in NB_D, and 0.5 ± 0.5º in OB_D. A two-way repeated measures ANOVA did not identify any significant main effect of block ($p = 0.85$, $\eta^2 < 0.001$) and endpoint ($p = 1.0$, $\eta^2 = 0.10$) as well as interaction of them ($p = 0.2$, $\eta^2 = 0.06$) (**Figure 3.8**).

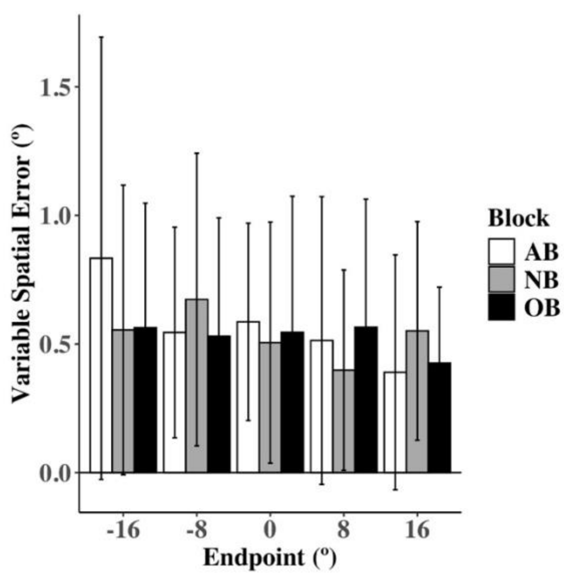


Figure 3.8. Variable spatial errors (VSEs) were not statistically different between the blocks and the endpoints.

The sample distributions of CTEs in all the three blocks were significantly skewed with Shapiro-Wilk tests (all $p < 0.001$). The entire CTE dataset was therefore log-transformed, and three outlying participants were excluded after the log-transformation (N = 24).

The sample distributions of ATEs in all the three blocks were significantly skewed with Shapiro-Wilk tests (all $p < 0.001$). The entire ATE dataset was therefore log-transformed to correct the sample distributions. No outlying subject was found using the interquartile range after the log transformation was performed (N = 27). The mean and standard deviations for ATE were 0.2 ± 0.2s in AB_D, 0.2 ± 0.1s in NB_D, and 0.2 ± 0.1s in OB_D. A two-way repeated measures ANOVA identified a large main effect of block ($p = 0.03$, $\eta^2 = 0.13$), while no significant main effect of endpoint ($p = 0.46$, $\eta^2 = 0.03$) and interaction ($p = 0.67$, $\eta^2 = 0.03$) was found. However, a post-hoc pairwise t-test with Bonferroni correction did not find a significant difference in ATEs between the blocks (all $p > 0.05$) (**Figure 3.9A**).

The sample distributions of VTEs in all the three blocks were significantly skewed with Shapiro-Wilk tests (all $p < 0.001$). The entire VTE dataset was therefore log-transformed to correct the sample distributions. Two participants were excluded after this log-transformation as the data did not fall within the interquartile range. The mean and standard deviations for VTE were 0.02 ± 0.02s in AB_D, 0.02 ± 0.02s in NB_D, and 0.02 ± 0.02s in OB_D. A two-way repeated measures ANOVA did not identify any significant main effect of block ($p = 0.39$, $\eta^2 = 0.04$) and endpoint ($p = 0.52$, $\eta^2 = 0.03$) as well as an interaction ($p = 0.84$, $\eta^2 = 0.02$) (**Figure 3.9B**).

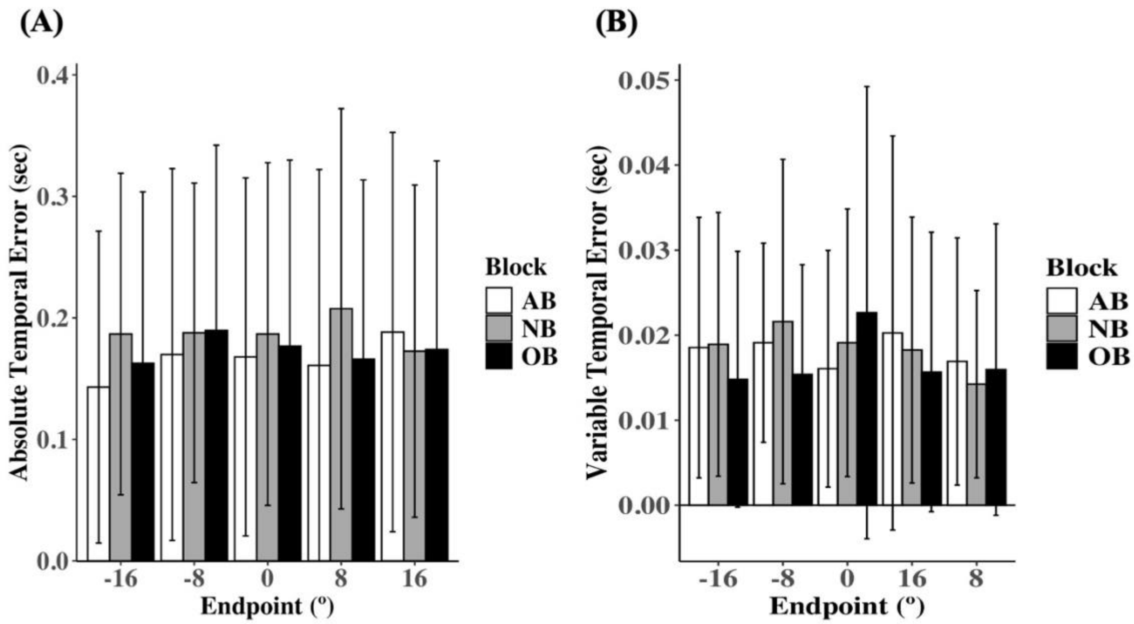


Figure 3.9. (A) Absolute temporal error and (B) variable temporal error in the dynamic reaching test as a function of the endpoints. No significant differences were found between the blocks or the endpoints ($p > 0.05$).

6.2.2. JPS test

The sample distributions of CEs in both AB_J and OB_J were not significantly skewed with Shapiro-Wilk tests ($p = 0.22$ and 0.35, respectively). Three outlying participants were excluded as they did not fall within the inter-quartile range (N = 24). The sample distributions of VPRS in both the JPS test and the dynamic reaching test were not significantly skewed with a Shapiro-Wilk test ($p = 0.18$ and 0.15, respectively). Three outlying participants were excluded as they did not fall within the inter-quartile range (N = 24).

The sample distribution of AE in AB_J was significantly skewed with Shapiro-Wilk tests ($p = 0.006$), while OB_J was not skewed ($p = 0.08$). The entire AE dataset was therefore log-transformed to correct the sample distributions. Two participants were excluded after this log-transformation as the data did not fall within the interquartile range (N = 25). The means and standard deviations for AE were 2.6 ± 1.5º in AB_J and 8.8 ± 2.6º in OB_J. A paired sample t-test identified a large effect of block in AE, with OB_J having a significantly larger AE than AB_J ($p <$ 0.001, $d = 2.9$) (**Figure 3.10A**).

The sample distribution of VE in AB_J was significantly skewed with Shapiro-Wilk tests ($p = 0.004$), while OB_J was not skewed ($p = 0.36$). The entire VE dataset was therefore log-transformed to correct the sample distributions. After this log transformation, four participants were excluded as the data did not fall within the interquartile range (N = 23). The means and standard deviations for VE were 0.5± 0.8º in AB_J and 1.6 ± 0.9º in OB_J. A paired sample t-test identified a large effect of block in VE, with OB_J having a significantly larger VE than AB_J ($p <$ 0.001, $d = 2.4$) (**Figure 3.10B**).

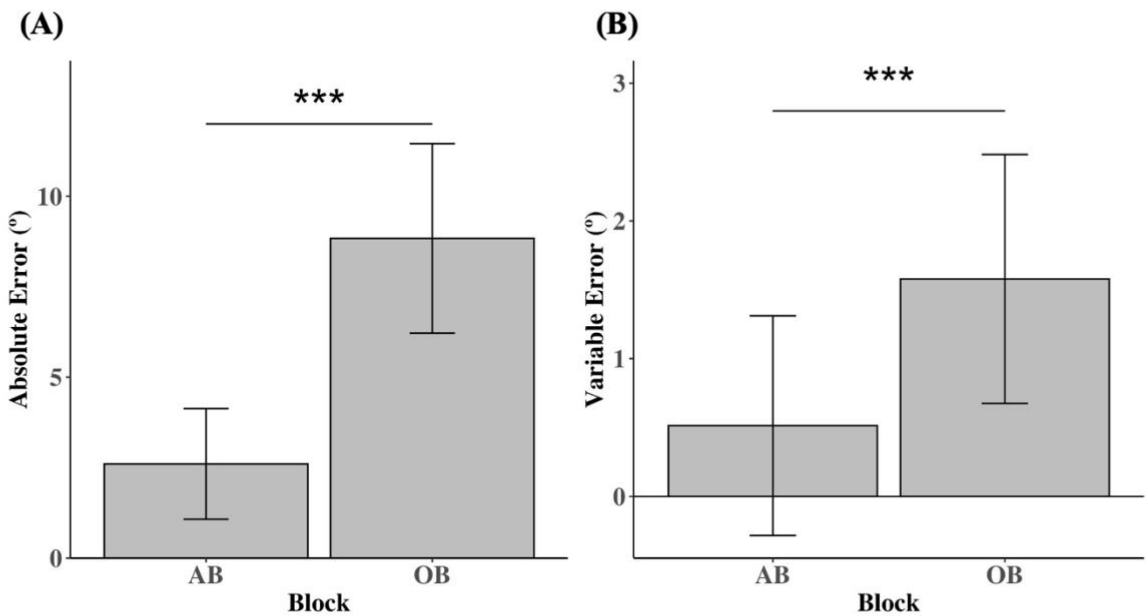


Figure 3.10. (A) Absolute error (AE) and (B) variable error (VE) in the joint position sense (JPS) test were larger in OB than AB. *** $p < 0.001$

CHAPTER IV

SHOULDER JOINT POSITION SENSE BETWEEN ATHLETES AND NON-ATHLETES, AS WELL AS FEMALES AND MALES IN VIRTUAL REALITY ENVIRONMENT

This work is currently in preparation for submission to the Journal of Human Movement Science and is co-authored by Motoki Sakurai and Dr. Andrew R. Karduna. Motoki Sakurai contributed to study design, experimental work including data collection and analysis, and writing. Dr. Andrew R. Karduna contributed to study design, research mentorship, and editorial assistance.

1. Introduction

Vision and proprioception are the primary senses that the central nervous system (CNS) uses to execute arm reaching movements, such as picking up a coffee cup (Apker et al., 2011; Goodman & Tremblay, 2018). The optimal integration theory suggests that the two senses are weighted optimally to maximize arm reaching accuracy, where one is prioritized over the other depending on its availability and quality (Block & Bastian, 2011a; Ernst & Banks, 2002). While vision is the dominant sense in most arm reaching situations, including active shoulder joint position sense (JPS) testing (Morehead et al., 2017; Spitzley & Karduna, 2022), humans can increase their reliance on proprioception relative to vision when necessary (Goodman & Tremblay, 2018; Sakurai et al., 2024).

The shoulder JPS test is traditionally used to assess proprioceptive accuracy with eyes closed (Dover et al., 2003; Vafadar et al., 2015). In this test, individuals actively move their arm or have their arm passively moved to a target position, return to the starting position, and then attempt to reposition their arm to the target position without visual feedback. Previous studies have examined proprioceptive differences across populations, including throwing athletes (i.e., baseball and softball) compared to their sex-matched non-athletic controls (Badagliacco & Karduna, 2018; Dover et al., 2003; Nodehi-Moghadam et al., 2012), as well as non-athletic females compared to males (Echalier et al., 2019; Vafadar et al., 2015). While findings have been mixed, most studies indicate that throwing athletes may have worse shoulder proprioception than non-athletes due to increased glenohumeral joint laxity (Safran et al., 2001), whereas no significant sex differences in proprioception have been consistently observed (Echalier et al., 2019; Vafadar et al., 2015).

Visual functions in professional baseball athletes have been reported to be superior to that of non-athletes (Chen et al., 2021). Baseball athletes demonstrated better eye tracking ability and faster initiation of the eye movement, and those with superior visual function tend to have more successful athletic careers (Kirschen & Laby, 2021). Given that throwing athletes may have poorer proprioception but better visual function, their joint repositioning accuracy may be comparable to that of non-athletic controls. In contrast, sex differences in visual function remain inconclusive, despite findings suggesting differential brain activation patterns between females and males in response to detection of object motion (Liu et al., 2024; Vanston & Strother, 2017). Current literature suggests that healthy females and males possess comparable visual and proprioceptive abilities.

Virtual reality (VR) provides an innovative approach to assessing vision-proprioception integration in the shoulder JPS test by manipulating the visual field in VR while the individual's eyes remain open. "Visual offset" in VR environment presents inaccurate visual feedback, creating visuo-proprioceptive incongruency where individuals see their hand offset from its actual position. Previous studies from our lab implemented a visual offset during the active shoulder JPS test and found that physically healthy individuals tend to reposition their hand based on visual input rather than proprioception (Sakurai et al., 2024; Spitzley & Karduna, 2022). This VR-based JPS test design allows researchers to examine vision-proprioception integration mechanisms in different populations.

The purpose of the present study was to investigate the effect of inaccurate visual feedback (i.e., offset vision) on shoulder JPS, focusing on population differences in a VR environment. Baseball and softball athletes were compared to their respective control group, and female controls were compared to male controls. It was hypothesized that no significant difference in JPS performance would be observed between athletes and non-athletes or between females and males, both with and without the visual offset.

2. Methods

2.1. Participants

A total of one-hundred-twenty-three participants were recruited and all participants provided informed consent as approved by the University of Oregon Institutional Review Board. Participants were categorized into four groups—baseball, softball, male control, and female control (**Table 4.1**). Handedness was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). Control group participants were included only if they had no history of upper limb injuries, pain, neurological disorders, uncorrected impaired vision, or competitive baseball/softball experience within the past three years. They were matched with a corresponding athlete group based on age, sex, and throwing arm dominance. The third question, "throwing", from the Edinburgh Handedness Inventory was used to determine the control participant's throwing dominance. Additionally, all ten questions from the inventory were utilized to determine dominant side for the female-to-male comparison analysis.

2.1.1. Sex Difference Comparison

Thirty-seven females (Age: 19.6 ± 1.6 years, Height: 1.6 ± 0.1 m, Weight: 63.7 ± 11.3 kg, 7 left-handed dominant, 6 left-handed throwers) and thirty-seven males (Age: 20.0 ± 1.6 years, Height: 1.8 ± 0.1 m, Weight: 80.3 ± 14.0 kg, 7 left-handed dominant and throwers) were recruited. All participants in this analysis scored below −40 or above +40 on the handedness questionnaire, indicating a relatively strong dominance for either the left or right hand (Dragovic, 2004).

2.1.2. Sport Experience Comparison

The softball group included eleven collegiate softball athletes competing at varying levels, including National Collegiate Athletic Association (NCAA) Division I, National Association of Intercollegiate Athletics (NAIA), and National Club Softball Association (NCSA) (Age: 19.6 ± 1.2 years, Height: 1.7 ± 0.1 m, Weight: 70.4 ± 10.6 kg, 1 left-handed thrower). The baseball group consisted of thirty-seven NCAA Division I baseball athletes (Age: 19.6 ± 1.3 years, Height: 1.9 ± 0.1 m, Weight: 95.0 ± 9.3 kg, 7 left-handed throwers). The female and male control groups consisted of the same subject pools in the sex comparison analyses, who were matched with the respective athlete group by their sex, age, and throwing arm.

Table 4.1. Mean ± standard deviation of demographic information of participants in each group. Control groups for baseball and softball groups were matched based on age, sex, and throwing

arm. “Dominant Hand” in the table is the throwing arm for the athlete groups and the dominant hand for the control groups. Age difference between the groups was not significant ($p = 0.49$).

	Softball	Baseball	Female Control	Male Control
Sample Size (n)	11	37	37	37
Age (years)	19.6 ± 1.2	19.6 ± 1.3	19.6 ± 1.5	20.0 ± 1.6
Sex (F/M)	F	M	F	M
Dominant Hand (R/L)	10 /1	30 / 7	30 / 7	30 / 7
Height (m)	1.7 ± 0.1	1.9 ± 0.1	1.6 ± 0.1	1.8 ± 0.1
Weight (kg)	70.4 ± 10.6	95.0 ± 9.3	63.7 ± 11.3	80.3 ± 14.0
Baseball / Softball Experience	Yes	Yes	No	No

2.2. Experimental Setup

Participants were outfitted with an HTC VIVE VR headset (2160 x 1200 resolution, PenTile OLED display) with headphones attached (HTC VIVE, Xindian District, New Taipei City, Taiwan) (*HTC VIVE Tracker (3.0) Developer Guideline Ver 1.1*, 2021). A wrist brace was fitted to their dominant arm and an HTC VIVE tracker (version 3.0) with Velcro tape was attached to the bottom of the tracker. Auditory instructions and cueing were delivered through the headphones. A 3D VR environment including a visual representation of the tested side wrist position in the space was displayed to the participant through the headset. Wrist position was projected as a baseball size black ball that matched the wrist tracker position in accurate vision block (AB) trials. In offset vision bock (OB) trials, this black ball position shifted +8º in the vertical axis for part of each trial using the arm length of each participant for this calculation. Wrist position was determined using output from the VIVE tracker, serving as the source of kinematic data for the current study (Spitzley & Karduna, 2019). All computations of wrist tracker projection with or without visual offset and data extraction during the JPS test were performed using C# scripts attached to a customized Unity program (Unity Technologies, San Francisco, CA).

2.3. Experimental Procedures

One trial of the JPS test consisted of two phases, the presentation phase and the replication phase. In the presentation phase, auditory cues guided participants to a target shoulder flexion angle. A low tone sound was emitted from the headphones when the arm was more than 5º below a target, and a high tone sound was emitted when the arm was more than 5º above a target. No sound was heard when the arm was within a 5º range of a target. The participant kept their arm at a target angle for 3 consecutive seconds and then moved it back to their side when the audible cue "relax" was emitted. The replication phase started 3 seconds after the end of the presentation phase. No auditory guidance regarding the arm angles was provided during this phase. Participants moved their arm to the remembered target and kept it at the target angle for 3 consecutive seconds until another "relax" cue was emitted. A visual representation of the wrist was displayed throughout the entire JPS trial. Further details of the JPS test paradigm can be found in a previous study from our lab (Spitzley & Karduna, 2022).

Two blocks (AB and OB) of 6 JPS trials were performed per upper limb in the randomized order across all participants. Within each block, the target angles 85, 90, and 95º were tested in a randomized order. In AB, the wrist position displayed in the VR environment was always congruent with the actual wrist position in the real-world space throughout this block. In OB, + 8º visual offset was introduced in the replication phase wherein the participant saw their wrist at 98º of shoulder flexion position when they flexed their shoulder to 90º. Both limbs were tested separately for each participant with a randomized order of AB and OB.

2.4. Data Extraction

Shoulder flexion angles were calculated with respect to vertical (the 0º starting position of the tracker). Mean shoulder flexion angles in the presentation and replication phases were calculated by averaging 100 data points prior to each "relax" cue. The following equations were used for each trial (i):

$$Constant\ Error\ (CE) = \theta_m = \left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e) \qquad \textbf{(Eq.4.1)}$$

$$Variable\ Error\ (VE) = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e - \theta_m)^2} \qquad \textbf{(Eq.4.2)}$$

θ_e is the repositioning error between the presentation angle and the replication angle, and n is the number of trials performed within a block. Absolute Error (AE) is the mean of the absolute repositioning errors, which reflects the magnitude of the repositioning errors. Vision-Proprioception Reliance Score (VPRS) was estimated using the following equation:

$$VPRS = -\left(\frac{CE_{OB} - CE_{AB}}{8}\right) \qquad \textbf{(Eq.4.3)}$$

The difference in CE between OB and AB was divided by 8, which was the magnitude of the visual offset introduced in OB, to scale the ratio of CE between the blocks to a range of zero to one. A VPRS of 0 indicates complete reliance on proprioception, with no influence of vision, while a VPRS of 1 indicates complete reliance on vision.

2.5. Statistical Analyses

The effect of block (AB vs. OB), tested arm side (dominant vs. non-dominant), and participant groups (athletes vs. non-athletes, female vs. male) on the repositioning error variables (CE, AE, and VE) were examined using three-way ANOVAs. For VPRS, the effects of arm side and group were examined using a two-way ANOVA. If a significant main effect or interaction was observed, pairwise t-tests with a Tukey correction were performed for *post-hoc* testing. For all the statistical tests, the alpha level was set at 0.05. Effect size η^2 was calculated for each of main effects and interactions in ANOVAs. η^2 of 0.01, 0.06, and 0.14 indicate small, medium, and large effect, respectively. All statistical analyses were performed using R 4.5.0 (R Core Team).

3. Results

For CE, a large main effect of the block were found ($F_{(1,118)} = 1354.1$, $p < 0.001$, $\eta^2 = 0.9$), where the participants significantly undershot a target shoulder flexion angle and exhibited worse repositioning errors in OB than AB. No other interaction or main effect was found (*Fs* < 2.9, *ps* > 0.1). The mean and standard deviation of CE across all the groups and both arms were −0.9 ± 1.8º in AB and −7.9 ± 2.7º in OB (**Figure 4.1**).

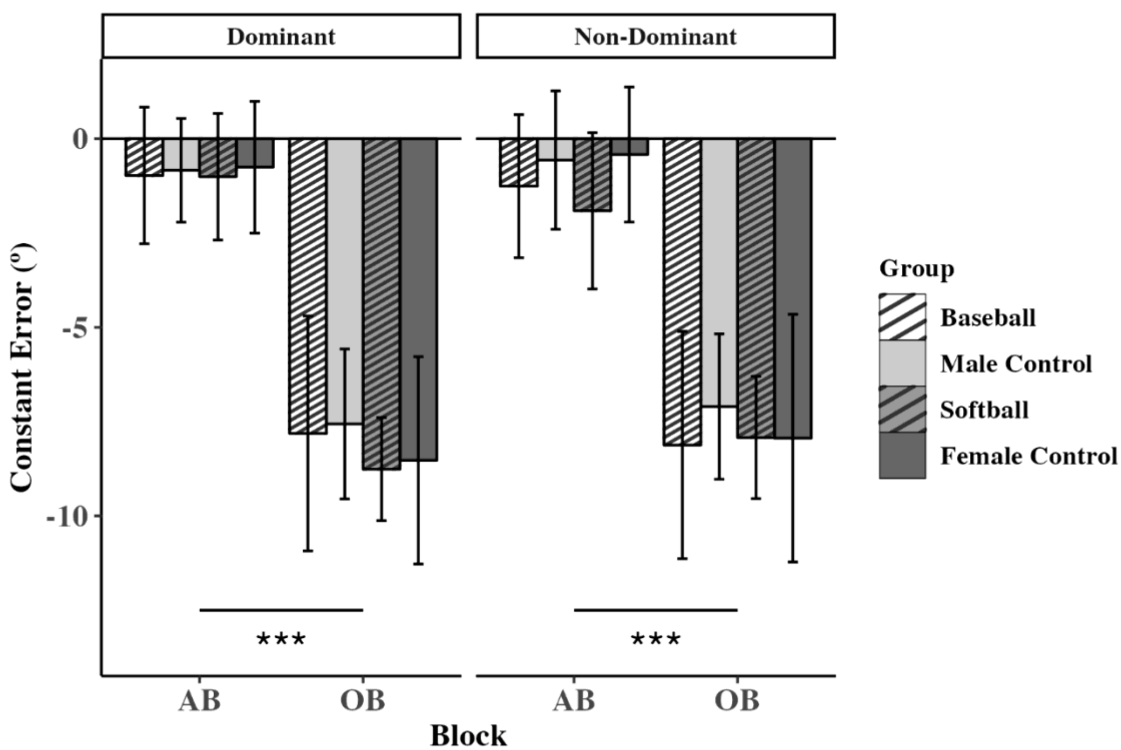


Figure 4.1. Constant errors (CEs). A large effect of the block was found ($p < 0.001$) without any other effect or interaction. *** denotes $p < 0.001$.

For AE, a medium three-way interaction among group, block, and side was found ($F_{(3, 118)} = 2.9$, $p = 0.04$, $\eta^2 = 0.07$). Post-hoc pairwise comparisons identified that AE in the non-dominant arm of baseball athletes was significantly larger in OB compared to male controls ($p = 0.02$). Similar to CE, a large main effect of block was observed ($F_{(1, 118)} = 890.9$, $p < 0.001$, $\eta^2 = 0.9$), with participants consistently showing greater AE in OB than in AB. No other significant main effects or interactions were detected (Fs < 2.3, *ps* > 0.1). The mean and standard deviation of AE across all groups and arms was 2.3 ± 1.2º in AB and 8.1 ± 2.2º in OB (**Figure 4.2**).

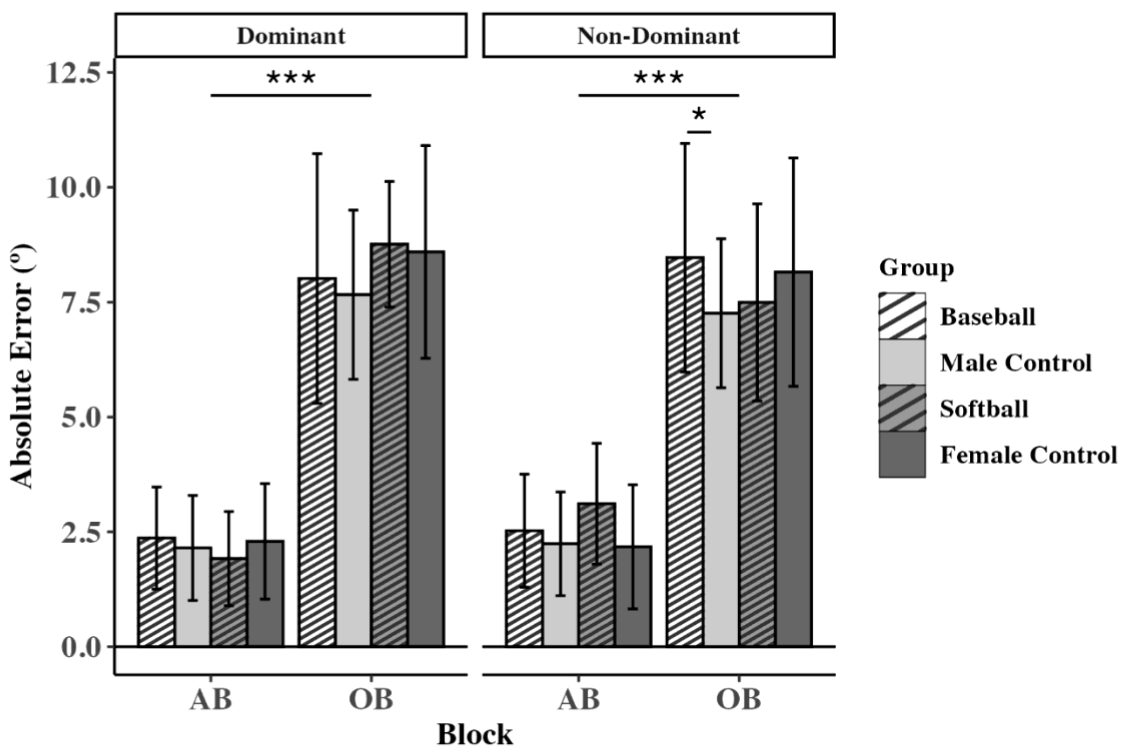


Figure 4.2. Absolute errors (AEs). Baseball athletes had a larger AE in their non-dominant arm and OB than male controls ($p = 0.02$). A large effect of the block was also found ($p < 0.001$). *** denotes $p < 0.001$. * denotes p < 0.05.

For VE and VPRS, no significant interaction or main effect was found across all conditions (*Fs* < 2.4, *ps* > 0.07 and *Fs* < 1.9, *ps* > 0.1, respectively). The mean and standard deviation of VE across all the groups and both arms were 2.24 ± 1.14º in AB and 2.32 ± 1.32º in OB (**Figure 4.3**). The mean and standard deviation of VPRS across all the groups and both arms were 0.88 ± 0.32 (**Figure 4.4**).

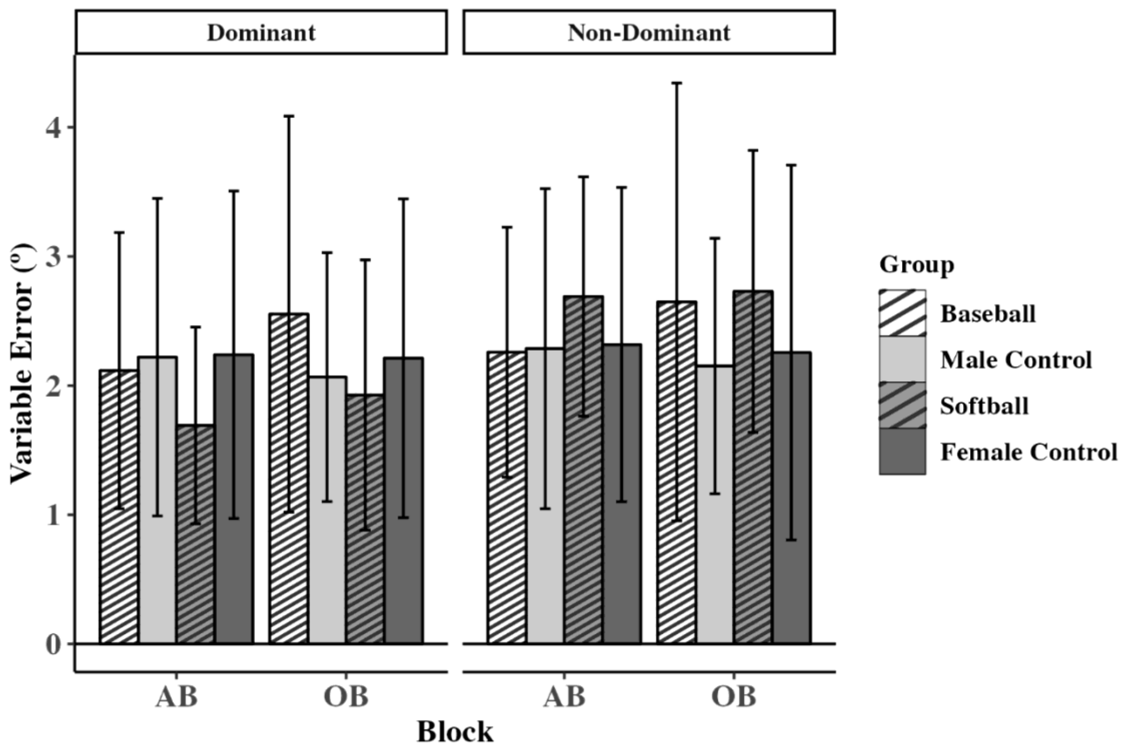


Figure 4.3. Variable errors (VEs). No significant main effect or interaction was found ($p > 0.05$).

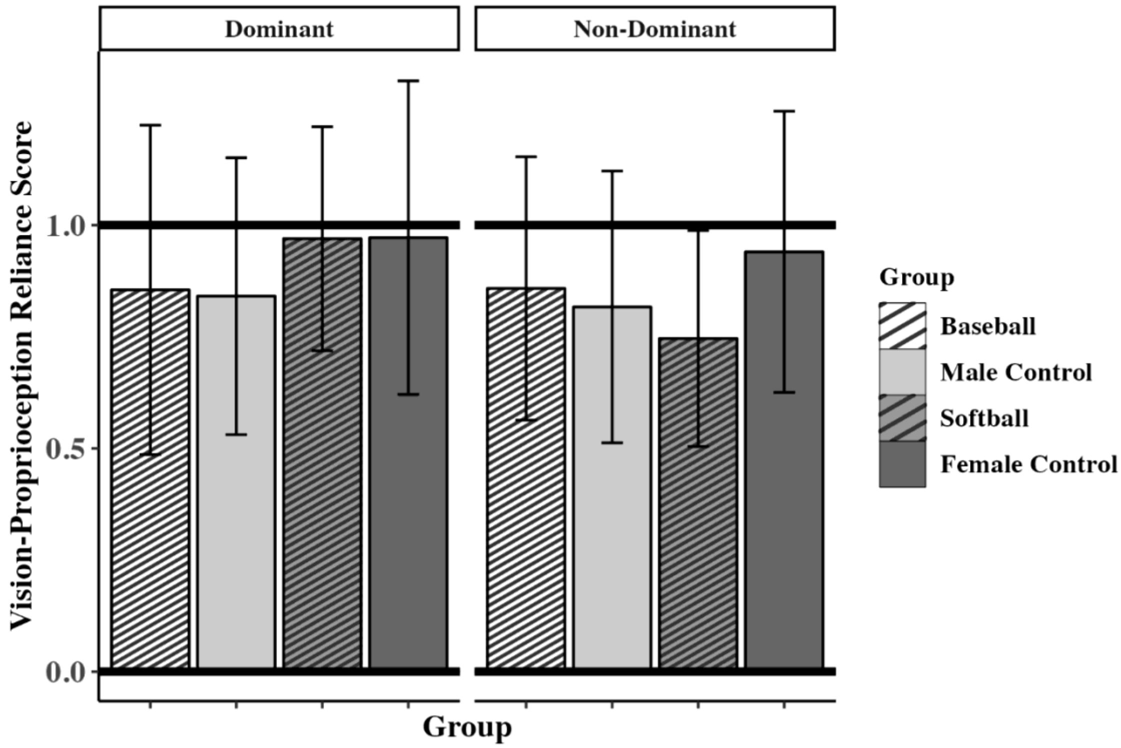


Figure 4.4. Vision-Proprioception Reliance scores (VPRSs) in 0-1 scale. No significant main effect or interaction was found (*p* > 0.05). All groups and both arms relied more on vision than proprioception in the current study (VPRS > 0.5).

4. Discussion

The purpose of this study was to investigate the effect of inaccurate visual feedback on shoulder JPS, focusing on population differences. The results largely supported our hypothesis, showing no difference between groups, except that baseball athletes exhibited greater AE compared to male controls during the OB when performed with the non-dominant arm. This study is the first to comprehensively evaluate shoulder joint repositioning accuracy and vision-proprioception integration across various populations and limb sides using immersive 3D VR technology.

Previous studies have reported inconsistent findings in the shoulder JPS accuracy with between overhead athletes and non-athletes, as well as between females and males, particularly under eyes-closed conditions (Badagliacco & Karduna, 2018; Dover et al., 2003, 2003; Echalier et al., 2019). The current study found that such differences largely disappeared when visual feedback was provided, except for AE. Specifically, a previous study reported overshooting (more positive CE) in females, and greater VEs in males during eyes-closed active shoulder JPS tasks (Vafadar et al., 2015). In contrast, these trends were not observed in the current study with eyes-open conditions in VR, as all groups consistently undershot the target angle (negative CE), and no increased VE was found in male controls. These results extend the current literature by demonstrating that different demographic groups (athletes vs. non-athletes, females vs. males) achieve comparable JPS accuracy in both limbs when provided with visual feedback, whether accurate or offset. This outcome likely results from the vision-dominant nature of the active shoulder JPS task used here, indicated by vision-proprioception reliance scores (VPRS) consistently above 0.5 across all groups and limbs (mean VPRS: 0.9). The strong visual dominance observed aligns with findings from prior research (Sakurai et al., 2024; Spitzley & Karduna, 2022). The strong reliance on vision may have masked potential proprioceptive differences among individuals and between limbs previously reported in the literature. However, the absence of a no-vision block (NB) that does not provide vision about hand in our protocol limits conclusions regarding whether the participants in the current study possessed inherent differences in their proprioceptive function.

Although most of the repositioning errors were not different between the demographic groups, AE was significantly greater in baseball athletes compared to male controls during the OB condition when the JPS test was performed with the non-dominant arm. However, no significant differences in AE were observed between groups in AB for the non-dominant arm, nor in either block for the dominant arm. This suggests that the visual offset introduced in the

OB condition may have had a more pronounced impact on baseball athletes specifically, particularly in their non-dominant arms used for catching the baseball. Previous research has indicated that motor control is adaptable, with elite athletes demonstrating unique motor control strategies in tasks requiring postural control (Paillard, 2017). Baseball athletes may develop specialized motor strategies in their non-dominant arm, enhancing flexibility and visual compliance to optimize ball-catching accuracy, as they frequently adjust hand positioning based on visual cues about ball location and trajectory. Furthermore, baseball athletes have been shown to possess superior visual function for accurate object tracking compared to non-athletes (Chen et al., 2021). The observed greater AE in baseball athletes under this specific condition might result from unique motor strategies related to vision, proprioception, or an interaction of both. Notably, this trend was not observed in softball athletes, possibly due to inconsistent playing levels or the smaller sample size of this group. Future studies should include larger size of softball athletes from elite level teams (e.g., Division I college players) to further elucidate these observations.

Future studies are encouraged to examine if different populations show varied repositioning errors and vision-proprioception integration patterns under alternative test modalities. For instance, shoulder JPS tasks involving horizontal abduction and adduction might uniquely influence the different populations as such movements require more proprioception reliance than shoulder flexion and extension (Klein et al., 2018). Conscious effort to ignore visual offset could cause different results between the limbs as right and left arms integrate visual feedback differently due to the functionality differences between right and left hemispheres of the brain executing the arm movements (Apker et al., 2011). According to the optimal integration theory, many factors are known to influence the reliance on vision and proprioception (Block & Bastian, 2010), and VR is capable of projecting any visual field that researchers wish to have for their research. Expanding multisensory integration research using VR will further deepen our understanding of human motor control mechanisms.

Baseball and softball athletes regularly perform arm reaching to catch a ball, demanding precise integration of visual and proprioceptive information. However, existing literature indicates that motor cortex adaptations are generally specific to the trained tasks and might not transfer to different types of reaching tasks (Paillard, 2017; Proteau & Isabelle, 2002). Therefore, investigating whether overhead athletes differ from non-athletes in arm-reaching accuracy and sensory reliance during tasks closely resembling ball-catching scenarios is important. Although our JPS findings provide fundamental insights into motor control patterns, sport-specific tests simulating realistic ball-catching situations may yield additional valuable insights. VR technology can replicate these dynamic scenarios and accurately measure arm-reaching performance. Ultimately, such assessments could aid scouting and talent identification processes by determining if successful athletes demonstrate superior multisensory integration compared to their less successful counterparts. Currently available motor assessments typically evaluate isolated visual functions or utilize two-dimensional ball interception tasks on screens, lacking specificity to realistic ball-catching or hitting actions (Chen et al., 2021; Kirschen & Laby, 2021; Laby et al., 2018).

The current study is not without limitations. Due to a time restriction with the athlete group data collections, we were not able to include NB besides AB and OB. NB would have been able to provide proprioceptive accuracy of each group and provide a baseline value without influence of vision on JPS test performance. However, it has been reported that CE in AB and NB were not different in the dataset containing both male and female participants in one of the our previous work using the same JPS protocol (Spitzley & Karduna, 2022). The sample size of the softball group (N = 11) was much smaller than the other three groups due to a difficulty in recruiting. Their playing level varied between NCAA Division I, NAIA, and NCSA as well, whereas the baseball athletes all play at NCAA Division I. This might have affected their performance in the JPS test in the current study. The HTC tracker was placed on the dorsal wrist, and the hand position was projected based on the tracker position. Although its effect is considered minimal as the visual offset was in the vertical direction, the participant saw their hand representation 1-2 cm lateral from their actual hand position.

In conclusion, the current study investigated the effect of visual offset on repositioning accuracy and vision-proprioception integration at an active shoulder JPS test in a 3D VR environment. It was found that both dominant and non-dominant upper limbs of the overhead athletes and non-athletes all showed similar results that vision was the dominant sense over proprioception while most of the repositioning errors were also not significantly different between groups and limb sides. Future studies are warranted to investigate whether this trend stays true when the multi-sensory integration is examined with baseball/softball specific situations mimicking catching or hitting a moving ball.

5. Bridge

The study outlined in this chapter investigated the effect of offset vision at the shoulder JPS test on different populations and limb sides. All repositioning error variables and VPRS were not statistically different between the groups including baseball/softball athletes and male/female controls. The results in the current chapter serve as a benchmark for each population of individuals. In Chapter V and VI, a revised novel dynamic reaching test is performed by the same participants. The dynamic reaching test in Chapter III will be updated based on its findings to better answer research questions in the following chapters. Chapter V focuses on sex difference between female and male controls, while Chapter VI focuses on differences between the athletes and the controls.

CHAPTER V

SEX DIFFERENCE IN DYNAMIC REACHING PERFORMANCE IN VIRUTAL REALITY

This work is currently in preparation for submission to the Journal of Human Movement Science and is co-authored by Motoki Sakurai and Dr. Andrew R. Karduna. Motoki Sakurai contributed to study design, experimental work including data collection and analysis, and writing. Dr. Andrew R. Karduna contributed to study design, research mentorship, and editorial assistance.

1. Introduction

Optimal integration theory proposes that the relative reliance on these sensory inputs are context-dependent and weighted optimally to maximize reaching accuracy for a given situation (Ernst & Banks, 2002), with vision typically dominating in "static" reaching tasks such as picking up a coffee cup on a table (Goodman & Tremblay, 2018; Spitzley & Karduna, 2022). One of our previous works using a "dynamic" reaching test, however, identified that proprioception is a dominant sense to track reaching hand movements when reaching for a ball coming at research participants in a three-dimensional (3D) virtual reality (VR) environment (Chapter III). Given that vision-proprioception reliance changes flexibly, it would be interesting to further investigate whether it differs between females and males, as well as dominant and non-dominant hand.

Although no sex or limb side differences were found in our static reaching test with the shoulder joint position sense (JPS) test (Chapter IV), previous studies have identified differences in arm-reaching performance in dynamic reaching tests (Apker et al., 2015; McGivern et al., 2012; Xiao et al., 2019). Females exhibited larger reaching errors than males in a task requiring participants to predictively point to the endpoint of a moving ball whose trajectory was occluded for the last 100 milliseconds (McGivern et al., 2012). Another study found no significant sex differences in reaction times in a single-arm reaching task (Mickevičienė et al., 2011). These findings suggest sex-based differences in brain activation patterns and visual perception during object motion detection (Liu et al., 2024; Vanston & Strother, 2017). However, it is still unclear whether sex difference exists in the relative reliance on vision and proprioception, besides reaching accuracy and temporal parameters such as reaction time or arm moving velocity. Furthermore, limb dominance has been shown to influence reaching accuracy and sensory reliance. In right-handed individuals, the dominant hand exhibited greater reliance on vision and demonstrated worse reaching accuracy compared to the non-dominant hand (Apker et al., 2015; Xiao et al., 2019). The potential interaction between sex and dominant hand warrants further exploration, as previous studies have not fully examined this factor in the context of VR or ball-catching movements. By using a VR dynamic reaching test, the present study aims to determine whether prior findings on sex and handedness can be generalized to this dynamic reaching modality.

VR has emerged as a powerful tool for rehabilitation, training, and entertainment, offering immersive experiences that can enhance motor learning and movement performance. Understanding how different populations interact with VR environments is crucial, particularly when the goal is to improve motor function in patients, athletes, or the general population. The HTC VIVE VR system used in this study provides reliable kinematic data with its tracker attached to an upper limb (Spitzley & Karduna, 2019). The findings from this study could inform the development of targeted rehabilitation and training protocols using VR for diverse populations. Notably, this study is the first to examine whether vision and proprioception are integrated differently between sexes and limb dominance in a 3D dynamic reaching task, expanding upon our prior work on static reaching (Chapter IV).

The purpose of the present study was to identify whether vision-proprioception integration mechanisms during a dynamic reaching test differs between sexes and limb dominance. It was hypothesized that males would exhibit lower reaching errors than females, while reaction times would not be significantly different between sexes or limb sides. Additionally, it was hypothesized that the dominant arm would rely more on vision compared to the non-dominant arm.

2. Methods

2.1. Participants

Thirty-seven females (Age: 19.6 ± 1.6 years, Height: 1.6 ± 0.1 m, Weight: 63.7 ± 11.3 kg, 7 left-handed dominant) and thirty-seven males (Age: 20.0 ± 1.6 years, Height: 1.8 ± 0.1 m, Weight: 80.3 ± 14.0 kg, 7 left-handed dominant) without a history of upper limb injuries, pain, neurological disorders, uncorrected impaired vision, or competitive baseball/softball experience within the past five years participated in the current study. The two groups were matched by their age and dominant hand. All participants provided informed consent as approved by the University of Oregon Institutional Review Board and their handedness was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). All participants scored below -40 or above +40 on the handedness questionnaire, indicating a relatively strong dominance for either the left or right hand (Dragovic, 2004). Individuals scoring between ±40 were classified as ambidextrous and excluded from the study.

2.2. Experimental Setup

Participants were outfitted with an HTC VIVE VR headset (2160 x 1200 resolution, PenTile OLED display) with headphones attached (HTC VIVE, Xindian District, New Taipei City, Taiwan). An HTC VIVE tracker (version 3.0) was placed on a wrist brace and a chest band to track dominant wrist and sternum kinematics, respectively. The wrist tracker was placed on the dorsal wrist, and the trunk tracker was placed on the approximate center of the xiphoid process. Auditory instructions and cueing were delivered through the headphones.

A custom 3D VR environment containing a room with plain walls and a visual representation of the participant's dominant hand were displayed to the participant through the headset. Hand position was projected as a baseball size black sphere positioned at the center of the wrist tracker. It served as a visual representation of the participant's hand in VR and the source of kinematic data for analysis. Although not visually projected in VR, the trunk tracker also provided kinematic data. A baseball size red sphere was also projected as a reaching target, which moved towards participants at their shoulder height at 5 m/s from 5 meters distance in front without a gravitational effect (no vertical displacement in ball trajectory) or curvature in its trajectory (**Figure 5.1**). All computations of target movements and data extraction were performed using custom C# scripts attached to a Unity program (Unity Technologies, San Francisco, CA).

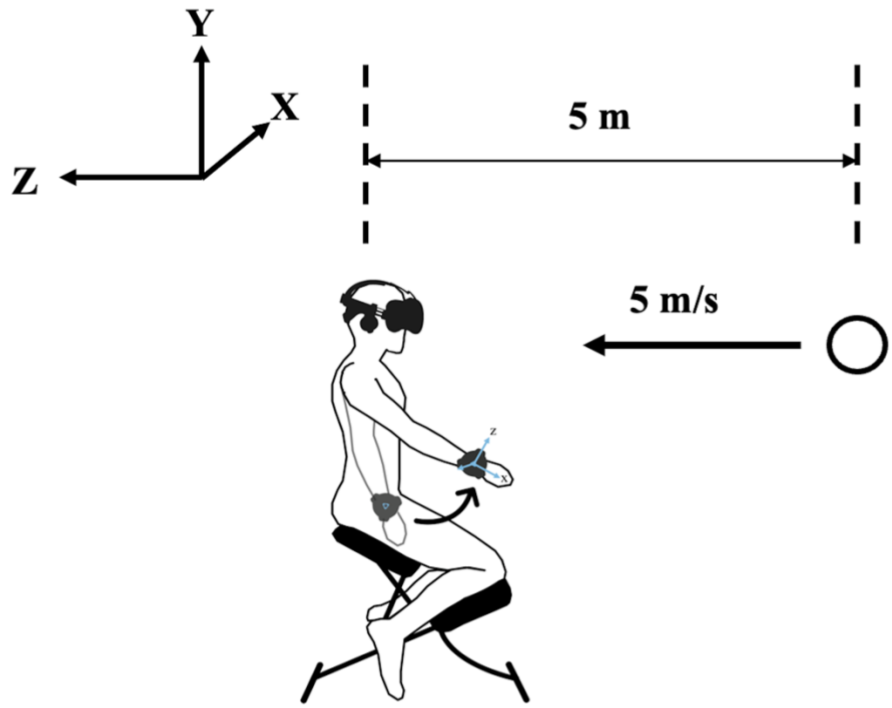


Figure 5.1. Reaching test setup. Participant is seated on a kneeling chair, wearing the headset with over-ear headphones. Trackers affixed to the dominant wrist and the sternum. The reaching target moves from five meters in front of the participant's dominant shoulder at five meters per second.

2.3. Experimental Procedure

For both the dynamic reaching and the JPS test, the participant was seated on a kneeling chair, allowing for full range arm motion while keeping an upright posture and minimizing chair oscillation during the experiments. The participant always started the trials with their tested arm relaxed at their side, the palmar side of the hand facing the medial direction, and the elbow fully extended. All shoulder elevation movements were a single joint shoulder elevation with the elbow fully extended. The participant's tested arm length from the top of the acromion process to the center of the wrist tracker was measured by placing another HTC VIVE tracker on top of the acromion process before the experiments began. In the meantime, the dominant shoulder position was computed in a customized Unity program (Unity Technologies, San Francisco, CA) using the shoulder tracker position data to determine reaching target trajectories.

While the reaching target's initial position in VR was consistent at 5 meters in front of the dominant shoulder position in all trials, the reaching target trajectories varied between three different endpoints among 0º or ±16º in the horizontal plane around the dominant shoulder position between trials (**Figure 5.2**). The 0º endpoint was in front of the dominant shoulder position, and reaching towards it would result in pure shoulder flexion. Endpoints were defined as the interception point where the participant's hand (wrist tracker center) would contact the ball if the participant moved their hand to the reaching target at the correct timing (Su et al., 2014). However, the reaching target became invisible 0.1 seconds before the hand reached the target endpoints in order to prevent providing the participant knowledge about their reaching accuracy in each trial. Hiding the target right before the hand-target contact enabled us to test the reaching accuracy over trials while limiting learning effect from previous trials.

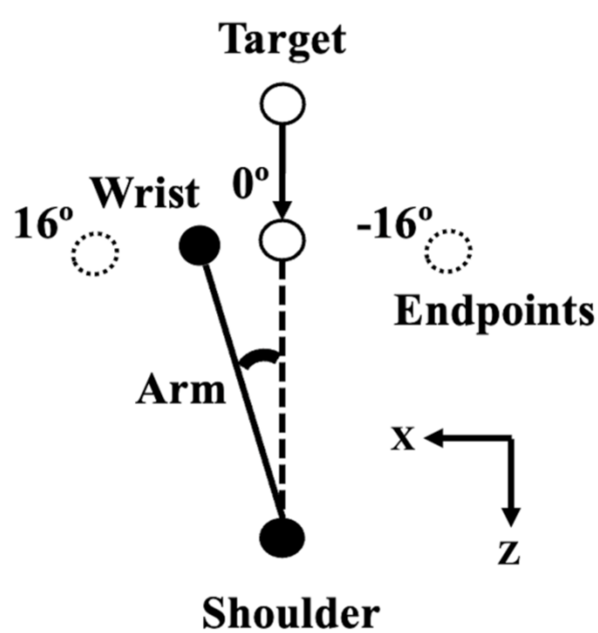


Figure 5.2. Coordinate system and spatial error in VR environment. Spatial error in each trial was angle difference between wrist tracker and target endpoint at a frame where the target reached to its endpoint. Endpoint in each trial was estimated from the participant's shoulder position and tested limb length.

The dynamic reaching test consisted of 30 trials in each of two blocks: accurate vision block (AB) and offset vision block (OB). Within each block, the first 21 trials were adaptation trials, and the last 9 trials were post-adaptation trials (**Figure 5.3**). Visual conditions differed between the blocks only in the adaptation trials, while the post-adaptation trials in each block were all performed with no visual information about the reaching hand position in VR. In AB, the tested hand position displayed in the VR environment was always congruent with the actual hand position in the real-world. In OB, the hand position was medially shifted by 8º with the participant's arm length taken into account. The task involved accurately hitting the moving target with a shoulder elevation movement. The order of target endpoints, block, and tested limb side were randomized across participants.

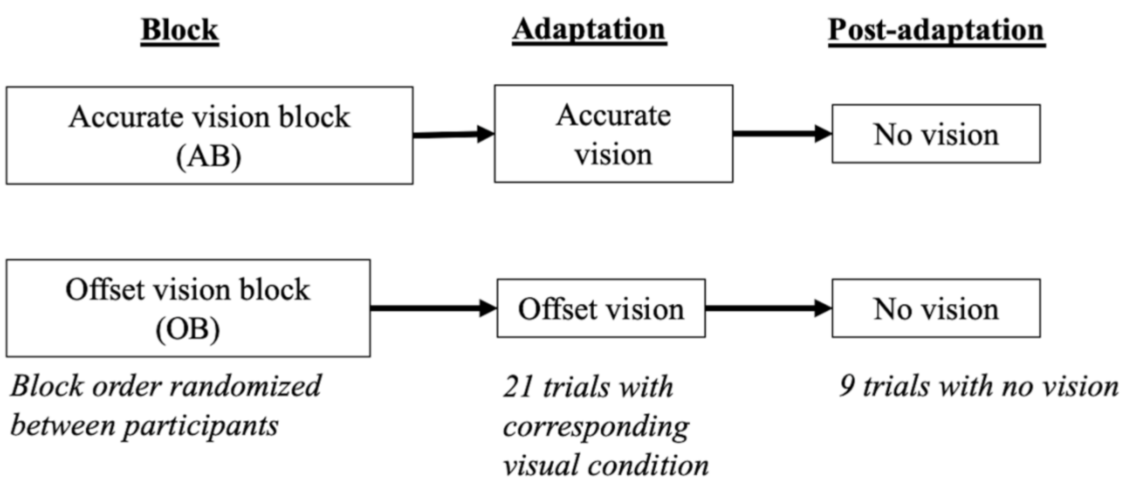


Figure 5.3. Flow of the dynamic reaching test. Visual representation of the reaching hand was projected at the accurate position in AB and was projected at the inaccurate position by 8º in OB_D during adaptation trials. In post-adaptation trials, the virtual hand position was not projected consistently regardless of what block the participant was performing.

2.4. Data Extraction

Kinematic data were sampled from the VIVE trackers at 90 Hz and collected using a customized Unity program during the dynamic reaching test. The 3D coordinate system for left hand trials were flipped and adjusted to be consistent with right hand trials. In the dynamic reaching test, hit rate was defined as the percentage of trials in which participants successfully hit the target with their reaching hand for each condition (block x tested limb × target endpoint). This metric was calculated to assess each participant's reaching accuracy. A hit was recorded when the target altered its trajectory as a result of a collision with the participant's visual hand in the VR environment. The constant spatial error (CSE) were calculated using the **Eq. 5.1** (King et al., 2013).

$$Constant\ Spatial\ Error\ (CSE) = \theta_m = \left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e) \quad \textbf{(Eq. 5.1)}$$

The spatial reaching error, θ_e, was the difference between the wrist tracker position and the target endpoint in degrees. (n) is the number of trials performed within a block and (i) is each trial. CSE defines the mean spatial reaching errors over the trials with directions, either positive or negative with respect to the target endpoint in the horizontal plane (mediolateral) (Morehead et al., 2017; Schroeger et al., 2021). Positive CSE values indicate that the reaching hand landed to the left of the target and negative values indicate it landed to the right, based on our VR environment's coordinate system (**Figure 5.2**). For left arm trials, the coordinate system was mirrored to align with that of the right arm, allowing for direct comparison across arms.

$$Absolute\ Spatial\ Error\ (ASE) = \left(\frac{1}{n}\right)\sum_{i=1}^{n}(|\theta_e|) \quad \textbf{(Eq. 5.2)}$$

Absolute spatial error (ASE) was calculated in the same way as CSE, except θ_e (spatial reaching error in each trial) was converted to absolute value for each trial. ASE defines the magnitude of the mean repositioning errors over the trials without taking the directions of errors into account.

$$Variable\ Spatial\ Error\ (VSE) = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e - \theta_m)^2} \quad \textbf{(Eq. 5.3)}$$

θ_m is CSE calculated using **Eq. 5.1**, and VSE defines the consistency of the magnitudes of the repositioning errors around the target angles, rather than the accuracy of the repositioning.

Vision-proprioception reliance score (VPRS) was estimated using **Eq. 5.4** (Spitzley & Karduna, 2022).

$$Vision - Proprioception\ Reliance\ Score\ (VPRS) = -\left(\frac{CSE_{OB} - CSE_{AB}}{8^{\circ}}\right) \quad \textbf{(Eq. 5.4)}$$

VPRS quantifies the participant's sensory reliance in the zero to one scale. In **Eq. 5.4**, CSE_{OB} is CSE in OB, CSE_{AB} is CSE in AB. A score of 1 indicated that participants placed their arm 8º towards the negative direction in X axis (to the right) in OB than AB, indicating that participants only used vision as 8º visual offset was seen in OB. A score of 0 indicated that participants placed their arm at the same position in X axis in both AB and OB, indicating participants only used proprioception.

Two temporal variables were included in the current study: response time and peak wrist velocity. Response time was the time difference between the initiation of the target movement and that of the arm. Target movement initiation was defined as the first frame that the Z coordinate of the target (anterior-posterior axis) differed from the previous frame. The initial arm movement was defined as the first frame that the wrist tracker was detected moving at above 0.2 m/s as its resultant velocity. Peak wrist velocity was defined as the peak resultant velocity of the wrist tracker once the tracker was detected moving at above 0.2 m/s.

2.5. Statistical Analyses

Four-way ANOVAs were performed for the dynamic reaching errors (CSE, ASE, VSE, response time, and peak wrist velocity) only in the post-adaptation trials to examine the main effects and interactions of group, limb side, block, and endpoint. Post-hoc pair-wise t-tests with Tukey correction were performed if the reaching errors were found statistically different between the conditions. For VPRS, three-way measures ANOVAs were performed on the last 10 trials of the adaptation trials as well as the post-adaptation trials by excluding the blocks from the independent variables, as VPRS was a ratio of CSE between AB and OB. This provided the data whether the adaptation occurred differently between groups or sides and whether the adaptation effect persisted during post-adaptation trials.

For all the statistical tests, the alpha level was set at 0.05. Effect size η^2 was calculated for each of main effects and interactions in ANOVAs. η^2 of 0.01, 0.06, and 0.14 indicate small, medium, and large effect, respectively (Adams & Conway, 2014). All statistical analyses were performed using R 4.5.0 (R Core Team).

3. Results

Mean and standard deviations of hit rate (%) were 93.5 ± 18.9 % in female control and 96.5 ± 13.2 % in male control. A main effect of endpoint was found ($p < 0.001$), while no other significant main effect or interaction was ($p > 0.1$). Post-hoc testing found that hit rate was significantly lower at the endpoints of ± 16º compared to 0º endpoint while no significant difference was found between +16º and -16º endpoints.

For CSE, participants had positive values at the lateral endpoint (−16°; mean = 4.8°) and negative values at the medial endpoint (16°; mean = −4.7°), indicating that they consistently hit the inner portion of the target at both endpoints (**Figure 5.4**). Statistically, a significant group-endpoint interaction was found ($p = 0.002$), requiring post-hoc pairwise comparisons. These identified that females had more positive CSE at −16° endpoint compared to males ($p < 0.001$), while no group differences were found at the endpoints 0° and 16° (*p*s = 0.2 and 1.0, respectively). In addition, significant main effects were found for block ($p < 0.001$) and side ($p < 0.001$). The main effects of block and side indicates that CSE was more positive in AB than in OB, and in the non-dominant arm than in the dominant arm. Although main effects of group ($p = 0.05$) and endpoint ($p < 0.001$) were found, the post-hoc testing for their interaction already described their relationships with CSE. Overall, more positive CSEs —indicating that the hand landed further to the left of the target—were observed in female participants for −16º (lateral) reaching, in AB, and with the non-dominant arm, relative to their respective counterparts.

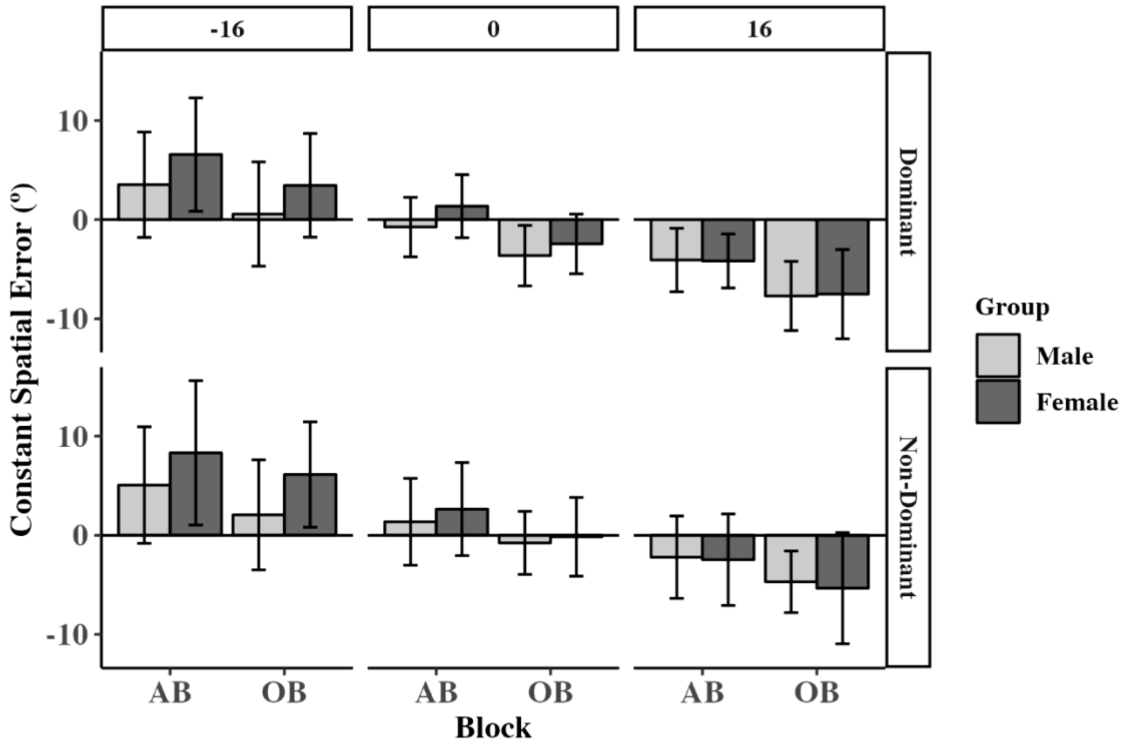


Figure 5.4. Constant spatial error (CSE). Main effect of group, block, endpoint, and tested arm and interaction between group and endpoint were found (all $p < 0.05$).

For VSE (**Figure 5.6**), no interactions or main effects reached significance (all *ps* > .20), except main effect of endpoint ($p < .001$). Post-hoc comparisons showed that VSE was significantly lower at the middle target (0°) compared to both endpoint −16° ($p = .002$) and endpoint 16° ($p = .005$), with no difference between the two outer targets ($p = .94$). This indicates that the magnitude of reaching errors was more variable at the medial and lateral endpoints across trials, whereas reaching to the middle endpoint was performed with greater reaching error consistency.

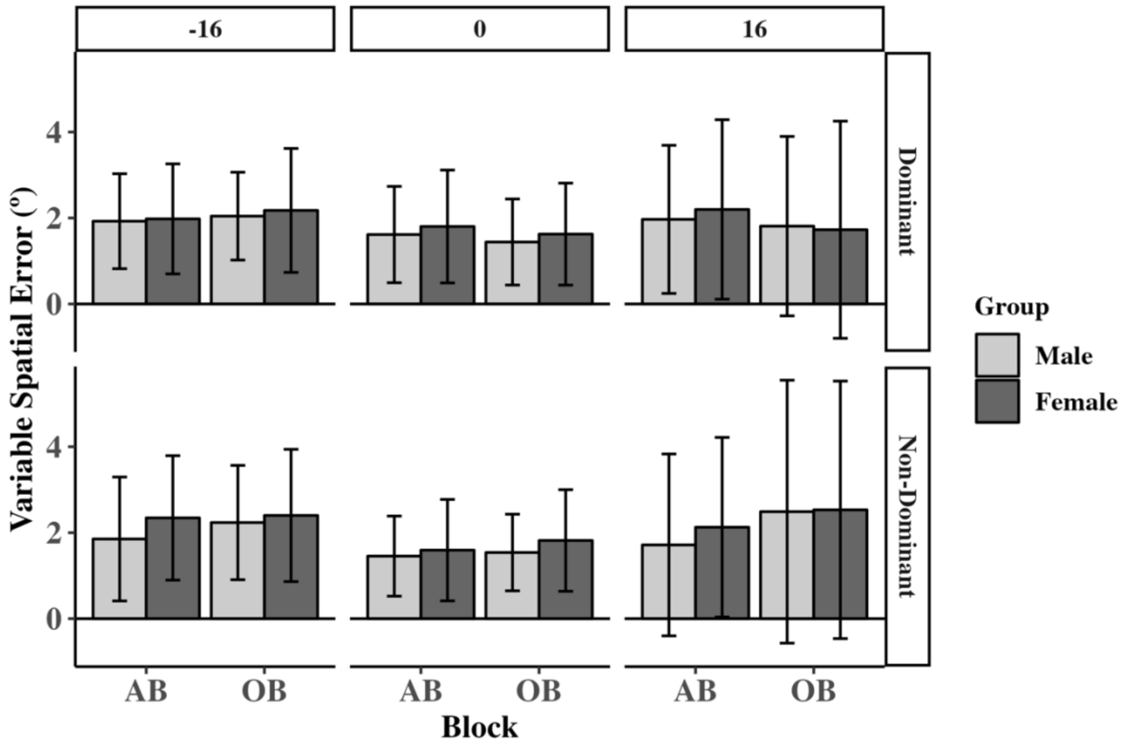


Figure 5.5. Variable spatial error (VSE). Reaching to middle (0º endpoint) had less variable (more consistent) reaching errors between trials compared to reaching to side targets (±16º) ($p < 0.005$).

For VPRS, no significant interactions or main effects were observed (**Figure 5.7**). The main effects of group ($p = 0.8$), limb side ($p = 0.2$), and endpoint ($p = 0.9$) were all non-significant. Likewise, no significant interactions were observed, including group-side, group-endpoint, side-endpoint, or group-side-endpoint (all *ps* > 0.3). Across all conditions, VPRS values remained below 0.5 in a zero to one scale, suggesting that participants were, on average, more reliant on proprioception than vision when tracking the position and movement of their reaching arm. However, between-participants variability was large relative to the mean value (mean ± standard deviation = 0.4 ± 0.5), indicating some of the participants were very strongly vision or proprioception dominant than others.

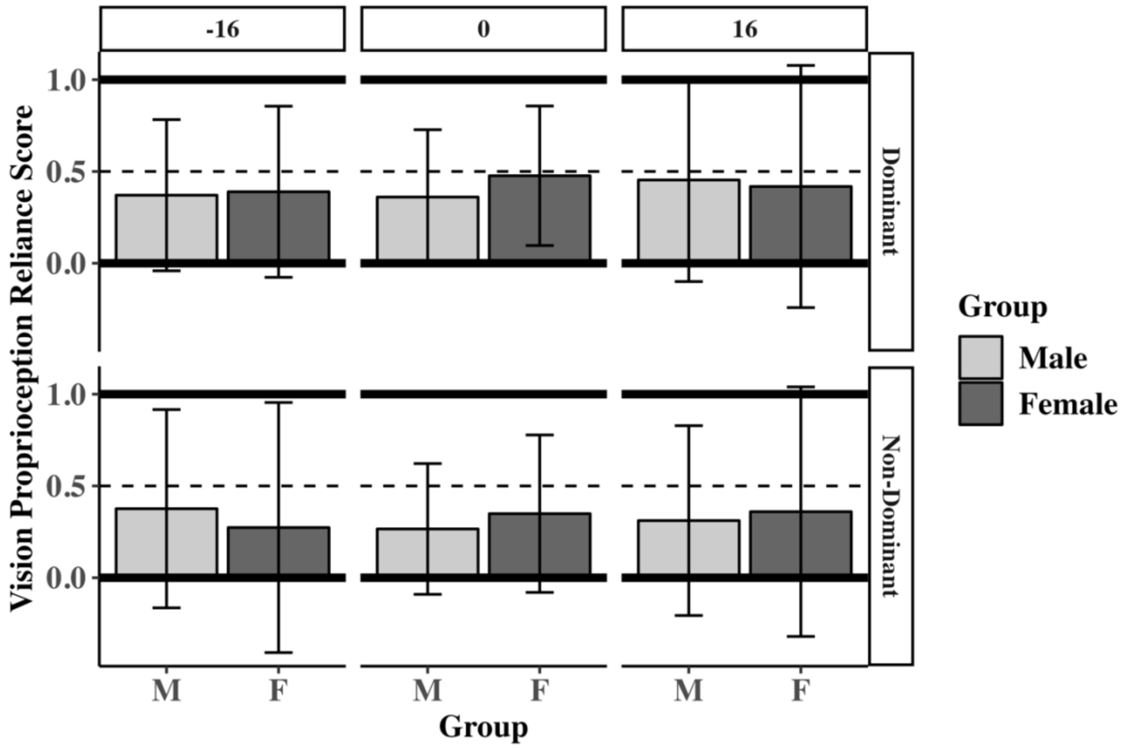


Figure 5.6. Vision-proprioception reliance score (VPRS). No significant difference was found ($p > 0.05$). Mean and standard deviation of VPRS across conditions were 0.4 ± 0.5.

For response time (**Figure 5.8**), no interactions reached significance (all *ps* > 0.1). Significant main effects were found for limb side ($p < .001$) and endpoint ($p = .001$). Participants initiated their arm movement quicker with their non-dominant side compared to their dominant side (0.33 vs. 0.36 seconds). Post-hoc comparisons also revealed that response time for the 16° endpoint was significantly faster than 0º endpoint (0.34 vs. 0.35 seconds; $p = 0.001$).

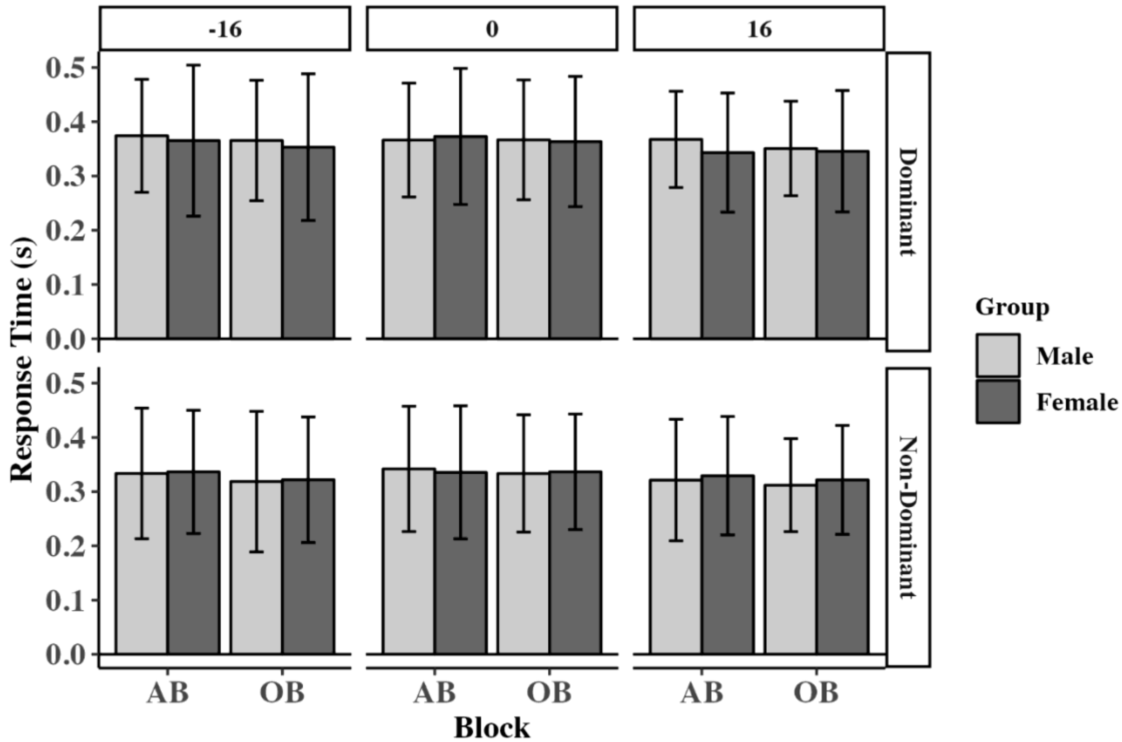


Figure 5.7. Response time. Non-dominant arm had a faster response time than dominant arm (p < 0.001). Reaching for the endpoint 16º had a faster response time than reaching for the endpoint 0º (p = 0.001).

For peak wrist linear velocity (**Figure 5.9**), no interactions reached significance (all *ps* > 0.2). A significant main effect of endpoint was found ($p < .001$), and post-hoc comparisons indicated that peak velocity was greater at endpoint 16° (3.0 m/s) compared to −16° endpoint (2.7 m/s; $p < .001$). P-values for the comparisons between 0° (2.6 m/s) and -16º, and between endpoints −16° and 0° were slightly above the set alpha level (both *ps* = 0.06). Combining the result with the response time, participants neither reacted quicker nor moved faster when reaching for the middle target at 0º, likely due to shorter distance to travel required for the middle endpoint compared to the medial and lateral endpoints.

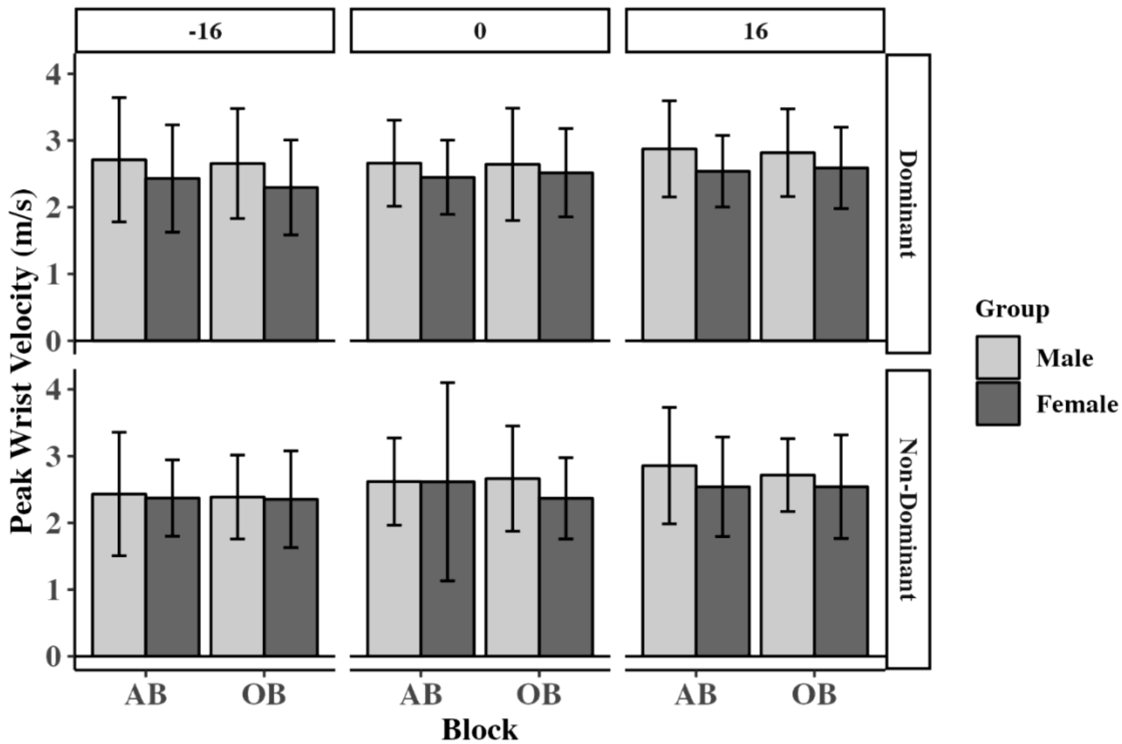


Figure 5.8. Peak resultant linear wrist velocity (m/s) was greater when reaching for the medial target (16º) than other two endpoints ($p < 0.001$).

In **Figure 5.10**, changes in spatial reaching error during the twenty-one adaptation trials in each group and limb are summarized. VPRSs from the last ten adaptation trials are also provided in **Figure 5.11**. Although statistic tests were not performed, the data visualized in the figures ensures that reaching error trended differently between AB and OB and indicates that different adaptation patterns have occurred between the two visual conditions before the participants started post-adaptation trials without vision of their reaching hand. In both limbs and groups (male and female), VPRS exceeded over 0.5 across all conditions (mean VPRS 0.7 for both males and females between limbs), indicating that participants relied more on visual hand than their perceived hand position from proprioception that are different from the post-adaptation trials (**Figure 5.7**).

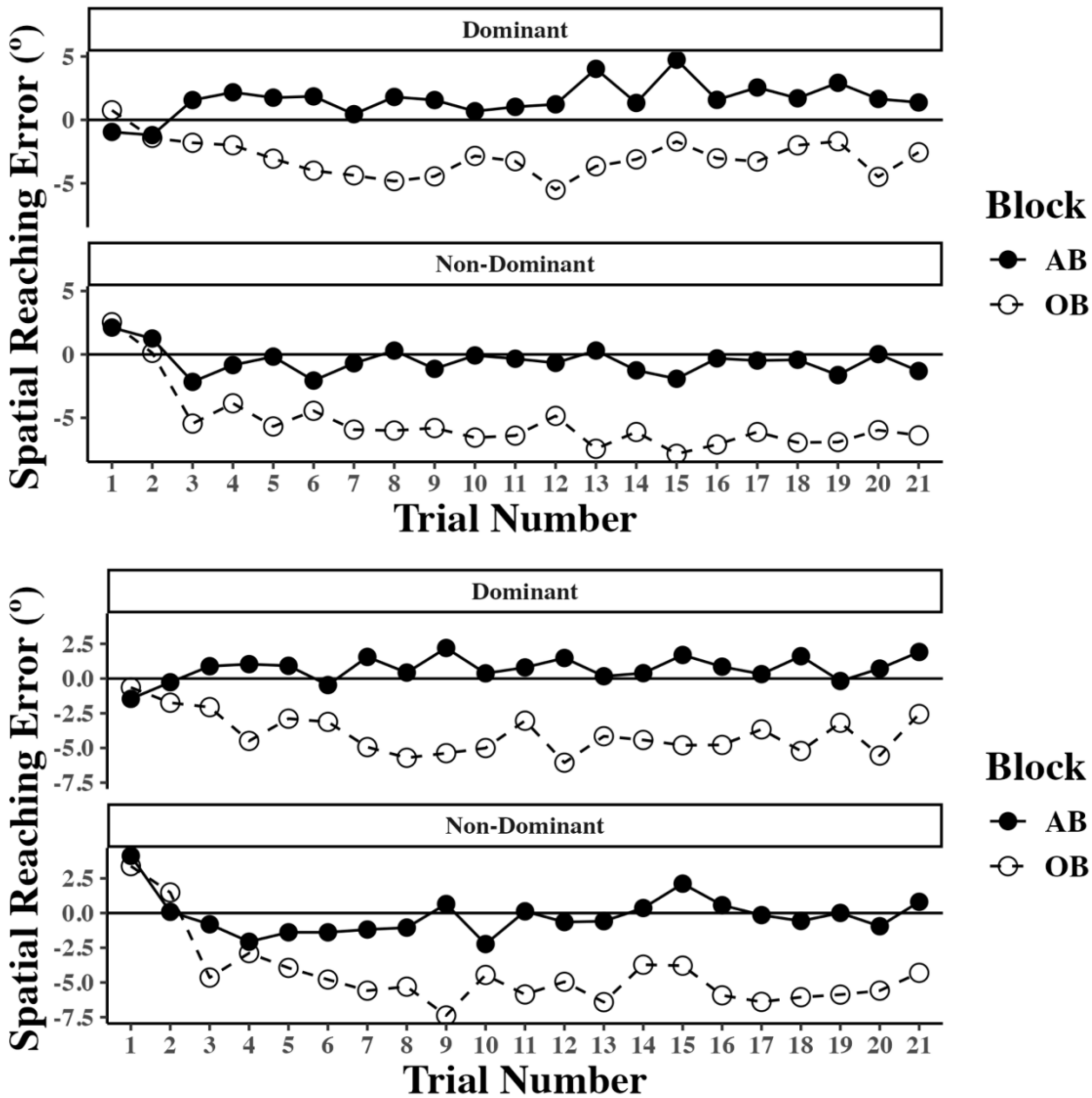


Figure 5.9. Spatial reaching errors in each adaptation trial 1-21. Top: female group. Bottom: male group.

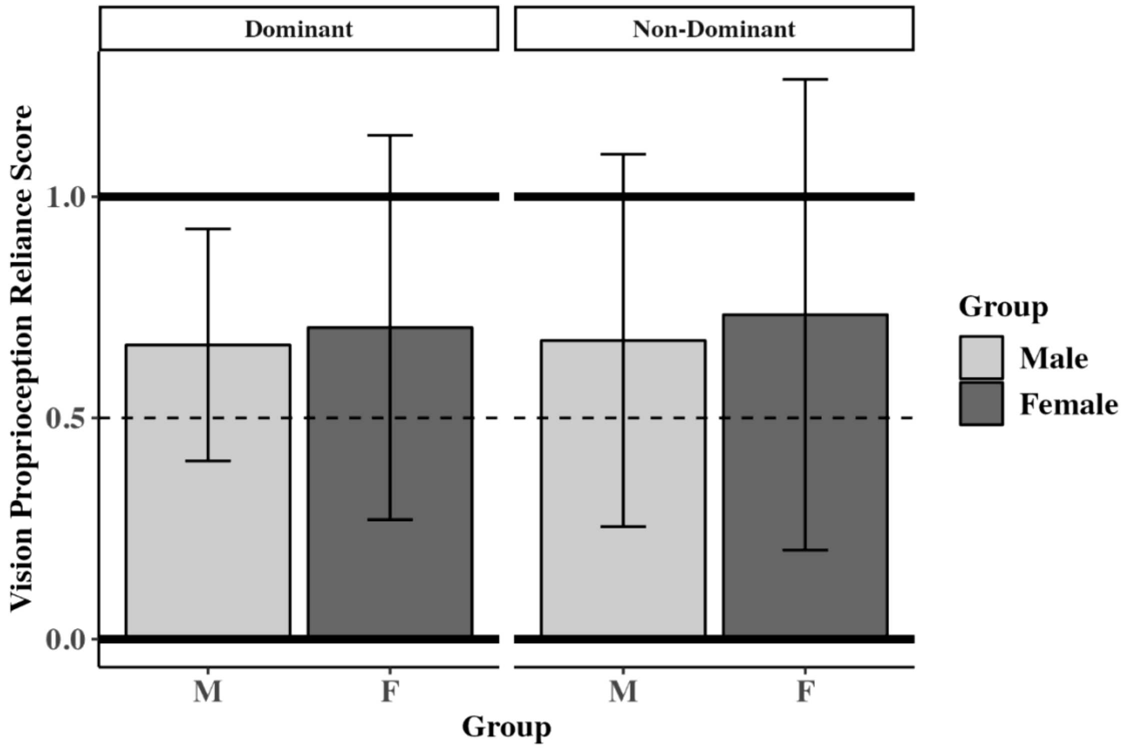


Figure 5.10. Vision-Proprioception Reliance Score (VPRS) from the last 10 trials of adaptation trials. The means for males and females across both limbs were 0.7, indicating vision dominant reaching.

4. Discussion

The purpose of the present study was to determine whether vision-proprioception integration mechanisms during a dynamic reaching test differ by sex and limb dominance. Our findings partially support the hypotheses, revealing complex relationships. Males exhibited more accurate reaching, noted by closer-to-zero CSEs, than females at the lateral endpoints (-16º), while hit rate and response times did not significantly differ between sexes. Furthermore, relative reliance on vision versus proprioception did not differ significantly by sex or limb dominance. Overall, significant sex difference only appeared in a small part of the current study design while males and females performed the task quite similarly across many variables of interest.

Results from CSEs suggest females made larger reaching errors than males when reaching for their lateral endpoint, while no sex difference was found at the other two endpoints. Smaller errors for males in this dynamic reaching task align with previous research emphasizing sex differences in spatiotemporal hand-eye coordination (McGivern et al., 2012). Sex-specific differences in visual information processing have been reported, with females more reliant on the ventral stream responsible for object recognition (e.g., shape and color), and males on the dorsal stream specialized in analyzing object movement (e.g., velocity and direction) (Goodale & Milner, 1992). Consequently, male participants may have benefited from enhanced movement analysis capability, particularly noticeable when reaching tasks became more complex at medial or lateral endpoints. Unlike middle endpoint reaches, diagonal arm movements to the lateral endpoint posed greater challenges, potentially amplifying male advantages in spatial processing. Additionally, although competitive baseball/softball experience within five years was an exclusion criterion, numerous participants had varied sport backgrounds. Previous literature suggests ball sport experience enhances upper limb motor control (Dalecki et al., 2019; Wei et al., 2024). More male participants reported experience in sports requiring dynamic upper limb movements, such as basketball, hockey, and water polo ($n = 34$ males vs. $n = 23$ females). Although a follow-up analysis did not find significant effects of such experiences on hit rate and CSE, previous exposure to dynamic arm-reaching sports among males might still partially explain their lower errors.

VSE was larger at the medial and lateral endpoints than the middle endpoint without significant differences between groups and limbs. Participants were more accurate and consistent (high hit rate and low VSE) when reaching for the middle endpoint, while the two side endpoints may have been more challenging to make accurate ball-hand contact for them. It was reported that both reaching accuracy and consistency lowers as task gets more difficult (Schroeger et al., 2021). Unlike previous reports identifying greater reaching variability among males during static tasks (Barral & Debû, 2004; Vafadar et al., 2015), our study showed no sex-related differences in dynamic reaching variability. It is likely that male participants were able to compensate their less consistent reaching accuracy by their superior analytic skill for moving object location and movement (Goodale & Milner, 1992).

VPRS, on the other hand, showed no significant difference across all conditions. These results were somewhat surprising but suggest that the influence of a visual offset on reaching errors were comparable across the sexes, limb sides, and endpoints. Participants consistently showed slight proprioception dominance over vision during post-adaptation trials (mean VPRS of 0.4), aligning with the findings from our previous study (Chapter III). In contrast, visual information about the hand was not integrated as strongly as in static reaching tasks described by earlier research, where vision typically dominates proprioception (Apker et al., 2011; Sakurai et al., 2024; Spitzley & Karduna, 2022). No sex differences emerged in VPRS, despite males demonstrating superior spatial reaching accuracy compared to females, as observed through CSE. Consistent with our previous findings from joint position sense tests (Chapter IV), both female and male participants exhibited similar VPRS patterns across limbs and endpoints. Although prior research suggests sex-related differences in visual information processing mechanisms or preferences (Goodale & Milner, 1992; Liu et al., 2024; Vanston & Strother, 2017), relative reliance on vision and proprioception were comparable between sexes. Limb differences were also not observed in VPRS, indicating that limb dominance did not influence relative sensory reliance and the other spatial accuracy measures (hit rate, CSE, and VSE). Limb dominance differences were primarily evident in timing-related variables, likely due to afferent signaling from the left hemisphere of the brain reaching the left arm faster compared to the right arm (Barral & Debû, 2004; Carson et al., 1995). This neurological timing difference did not appear to affect spatial reaching performance. Additionally, considerable between-participant variability in VPRS suggested individual differences in sensory reliance, with some participants entirely dependent on vision (VPRS of 1) and others completely reliant on proprioception (VPRS of 0). This variability likely reflects inherited sensory preferences independent of sex or limb dominance.

Response time was not different between females and males, which supports one of our hypotheses and aligns with previous studies testing with arm reaching tasks (Barral & Debû, 2004; Mickevičienė et al., 2011). One study that reported slower response time in female involved pressing a key in response to an object projection on a screen, which does not require accuracy of spatiotemporal movement coordination like arm reaching tasks (Der & Deary, 2006). However, response time was significantly faster in the non-dominant arm (left arms for 60 right-handed participants out of 74) than non-dominant arm in the current study. Advantage of left arm in response time has been the consistent finding across many studies (Barral & Debû, 2004; Carson et al., 1995; Mickevičienė et al., 2011) most likely due to the fact that the right hemisphere of the brain are specialized for vision-proprioception processing and body movement organization (Mickevičienė et al., 2011). In addition, response time was quicker and peak wrist velocity was faster when reaching for the two side endpoints than the middle endpoint without effect of sex. This makes sense as participants needed to move their arm longer distance to get to the side endpoints on time and faster reaction time and wrist velocity were required. However, it contradicts the results from a previous study that reported faster arm velocity only reaching for lateral targets (Barral & Debû, 2004). This could be due to a difference in movement planes as the reaching test was set up on a table in front of participants that are 2D while our dynamic reaching test was set up in 3D environment. Also, previous research report that movement crossing the middle line of the body require different arm joint coordination (Barral & Debû, 2004; Carson et al., 1995), causing slower response and arm velocity for medial target reaching. The medial target in the current study was not located across the midline as the three endpoints were spread around the shoulder position.

One of the limitations for the current study was the sample size. Although a fairy large number of participants were recruited for a human movement study, many more sample size would be required to maintain higher statistical power for four-way ANOVAs. However, it is worth mentioning that many of our findings had very large effect sizes. If more time was allowed for each participant, it would have been ideal to evaluate the effect of visual offset in both medial and lateral directions as very interesting endpoint-limb interaction was found. With only one-directional visual offset tested in the current study, we are not able to determine whether this interaction is caused by the computational limitation explained above or physiological responses from participants.

In conclusion, trivial sex and limb side differences were found in the current study. Females had larger reaching errors in CSE only at the lateral reaching target and slower response time potentially due to differences in the information processing mechanisms and/or unfamiliarity with ball catching movements compared to their male counterpart. Limb side differences were observed in response time, while differences in reaching errors were trivial. VR technologies enable to study vision-proprioception integration mechanisms and differences between the limbs and the sexes in 3D environment, while such motor control skills have been typically studied in 2D environment. Sex and limb differences in 3D reaching movements were found overlapped with 2D movements, whereas some of the findings in the current study provide unique findings that were different form 2D reaching studies. Future studies are encouraged to use VR to expand the scope of motor control studies and explore areas that are not investigated well.

5. Bridge

The study outlined in this chapter examined sensory integration patterns in a dynamic reaching test in virtual reality environment with the focus on sex difference and the limb side. Spatial reaching accuracy was greater in males than females, while no sex difference was observed in relative reliance on vision and proprioception. Both side of the limbs showed similar spatial reaching accuracy and relative sensory reliance. In temporal variables consisting of response time and peak wrist velocity, no sex difference was found, while non-dominant limb showed faster response time than dominant limb. Since non-dominant limb for most of the participants were left handed, the results indicate the advantage of sensory input processing for the left arm likely due to the brain function.

In Chapter VI, this dynamic reaching test is performed by baseball and softball athletes and compare their sensory integration patterns with male and female non-athletes. Limb side specific difference between athletes and non-athletes will also be examined to identify whether baseball and softball-athletes have unique motor control developed after extensive ball catching and hitting training through their sports.

CHAPTER VI

DYNAMIC REACHING PERFORMANCE IN VIRUTAL REALITY BETWEEN ATHLETES AND NON-ATHLETES

This work is currently in preparation for submission to the Journal of Human Movement Science and is co-authored by Motoki Sakurai and Dr. Andrew R. Karduna. Motoki Sakurai contributed to study design, experimental work including data collection and analysis, and writing. Dr. Andrew R. Karduna contributed to study design, research mentorship, and editorial assistance.

1. Introduction

Baseball and softball involve reaching for a dynamically moving ball when athletes catch or hit a ball. Elite athletes need to integrate vision and proprioception in their central nervous system precisely to execute such ball reaching movements at high accuracy. Optimal integration theory proposes that relative reliance on vision and proprioception are weighted optimally to maximize reaching accuracy for a given situation, while vision is typically a dominant sense over proprioception (Block & Bastian, 2011a; Goodman & Tremblay, 2018; Morehead et al., 2017). However, an environment that the baseball and softball athletes perform the arm reaching is in a 3D space and a ball typically is thrown or hit from their front. Only one of the previous works from our lab implemented this 3D AP reaching with dynamically moving reaching targets, "dynamic reaching test", using a VR system (Chapter III). No previous study has investigated the arm reaching accuracy of the baseball or softball players in an environment close to on-field ball reaching.

The current literature provides insights into how potentially the baseball and softball athletes perform the dynamic reaching test. Baseball players showed superior eye tracking ability than non-athletes (Chen et al., 2021). Successful baseball athletes are more likely to have better eye function (e.g., depth cue, eye tracking, etc.) than less successful baseball athletes (Kirschen & Laby, 2021). Moreover, position players showed better eye function than pitchers (Chen et al., 2021; Laby et al., 2018). On the other hand, the athletes' shoulder proprioceptive accuracy could potentially be altered due to accumulated microtrauma to proprioceptive receptors (joint capsules) at the throwing side shoulder joint (Myers et al., 2006; Safran et al., 2001). Studies comparing proprioception in shoulder JPS tests performed with eyes closed indeed identified worse joint repositioning accuracy in baseball and softball athletes than non-athletes (Badagliacco & Karduna, 2018; Dover et al., 2003). However, a previous work in our lab found no significant difference between the baseball and softball athletes and non-athletes in the shoulder JPS test performed with eyes open (Chapter IV). This indicates that altered proprioception in the athletes may be corrected by vision.

Such findings lead to another research question whether the vision-proprioception integration is not different even in more dynamic reaching movements involving ball catching like arm movements. In addition, multisensory integration mechanisms could show an interaction between the populations and the limb side as the baseball and softball athletes catch a moving ball with their non-throwing hand in their sports. Our previous work also found sex and limb side differences in some of the spatiotemporal variables in the dynamic reaching test (Chapter V). The current study further expands the investigation to the athlete versus non-athlete comparison. The purpose of this study was to investigate whether baseball and softball athletes possess different multisensory integration patterns than their controls in the dynamic reaching test in VR environment. It was hypothesized that the baseball and softball athlete groups would show smaller spatial reaching errors in their non-throwing arm, more sensory reliance on vision in their throwing arm, faster response time, and faster peak wrist velocity than the control groups.

2. Methods

2.1. *Participants*

A total of ninety-six participants were recruited and all participants provided informed consent as approved by the University of Oregon Institutional Review Board. Participants were categorized into four groups—baseball (n = 37), softball (n = 11), male control (n = 37), and female control (n = 11). Handedness was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). Control group participants were included only if they had no history of upper limb injuries, pain, neurological disorders, uncorrected impaired vision, or competitive baseball/softball experience within the past three years. They were matched with a corresponding athlete group based on age, sex, and throwing arm dominance. The third question, "throwing", from the Edinburgh Handedness Inventory was used to determine the participant's throwing dominance.

The baseball group consisted of thirty-seven NCAA Division I baseball athletes (Age: 19.6 ± 1.3 years, Height: 1.9 ± 0.1 m, Weight: 95.0 ± 9.3 kg, 7 left-handed throwers). The softball group included eleven collegiate softball athletes competing at varying levels, including National Collegiate Athletic Association (NCAA) Division I, National Association of Intercollegiate Athletics (NAIA), and National Club Softball Association (NCSA) (Age: 19.6 ± 1.2 years, Height: 1.7 ± 0.1 m, Weight: 70.4 ± 10.6 kg, 1 left-handed thrower). As control samples, thirty-seven males (Age: 20.0 ± 1.6 years, Height: 1.8 ± 0.1 m, Weight: 80.3 ± 14.0 kg, 7 left-handed dominant) and eleven females (Age: 19.6 ± 1.6 years, Height: 1.6 ± 0.1 m, Weight: 61.0 ± 11.0 kg, 1 left-handed dominant) were recruited as control samples.

2.2. *Experimental Setup*

Participants were outfitted with an HTC VIVE VR headset (2160 x 1200 resolution, PenTile OLED display) with headphones attached (HTC VIVE, Xindian District, New Taipei City, Taiwan). An HTC VIVE tracker (version 3.0) was placed on a wrist brace and a chest band to track dominant wrist and sternum kinematics, respectively. The wrist tracker was placed on the dorsal wrist, and the trunk tracker was placed on the approximate center of the xiphoid process. Auditory instructions and cueing were delivered through the headphones.

A 3D VR environment with customized Unity program (Unity Technologies, San Francisco, CA) containing a room with plain walls and a visual representation of the participant's dominant hand were displayed to the participant through the headset. Hand position was projected as a baseball size black sphere positioned at the center of the wrist tracker. It served as a visual representation of the participant's hand in VR and the source of kinematic data for analysis. Although not visually projected in VR, the trunk tracker also provided kinematic data. A baseball size red sphere was also projected as a reaching target, which moved towards participants at their shoulder height at 5 m/s from 5 meters distance in front without a gravitational effect (no vertical displacement in ball trajectory) or curvature in its trajectory (**Figure 6.1**). All computations of target movements and data extraction were performed using C# scripts attached to a customized Unity program.

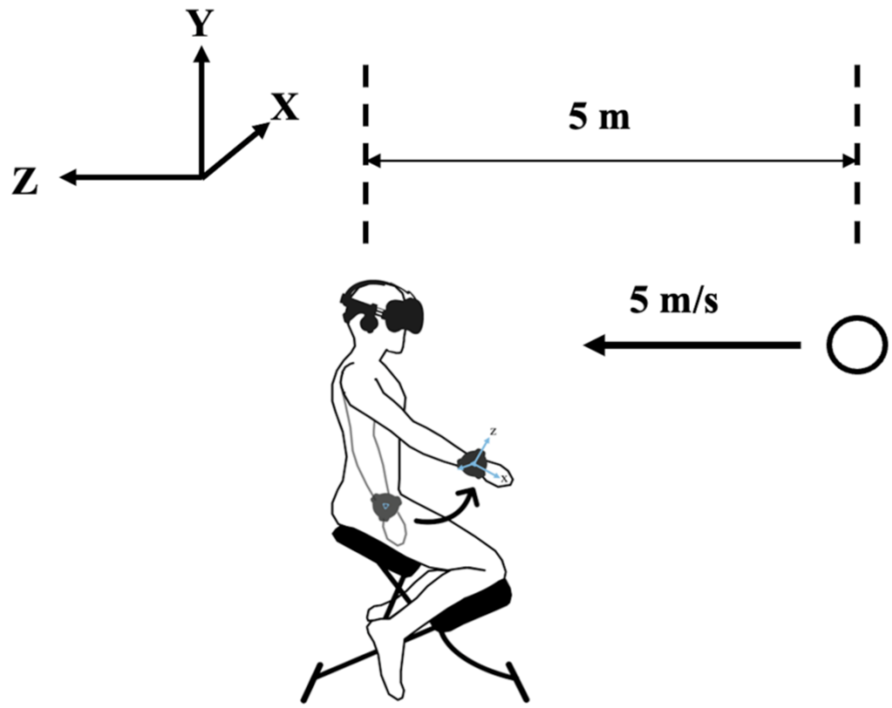


Figure 6.1. Reaching test setup. Participant is seated on a kneeling chair, wearing the headset with over-ear headphones. Trackers affixed to the dominant wrist and the sternum. The reaching target moves from five meters in front of the participant's dominant shoulder at five meters per second.

2.3. *Experimental Procedure*

The participant was seated on a kneeling chair, allowing for full range arm motion while keeping an upright posture and minimizing chair oscillation during the experiments. The participant always started the trials with their tested arm relaxed at their side, the palmar side of the hand facing the medial direction, and the elbow fully extended. All shoulder elevation movements were a single joint shoulder elevation with the elbow fully extended. The participant's tested arm length from the top of the acromion process to the center of the wrist tracker was measured by placing another HTC VIVE tracker on top of the acromion process before the experiments began. In the meantime, the dominant shoulder position was computed in a customized Unity program using the shoulder tracker position data to determine reaching target trajectories.

While the reaching target's initial position in VR was consistent at 5 meters in front of the dominant shoulder position in all trials, the reaching target trajectories varied between three different endpoints among 0º or ±16º in the horizontal plane around the dominant shoulder position between trials (**Figure 6.2**). The 0º endpoint was in front of the dominant shoulder position, and reaching towards it would result in pure shoulder flexion. Endpoints were defined as the interception point where the participant's hand (wrist tracker center) would contact the ball if the participant moved their hand to the reaching target at the correct timing (Su et al., 2014). However, the reaching target became invisible 0.1 seconds before the hand reached the target endpoints in order to prevent providing the participant with knowledge about their reaching accuracy in each trial. Hiding the target right before the hand-target contact enabled us to test the reaching accuracy over trials while limiting learning effect from previous trials.

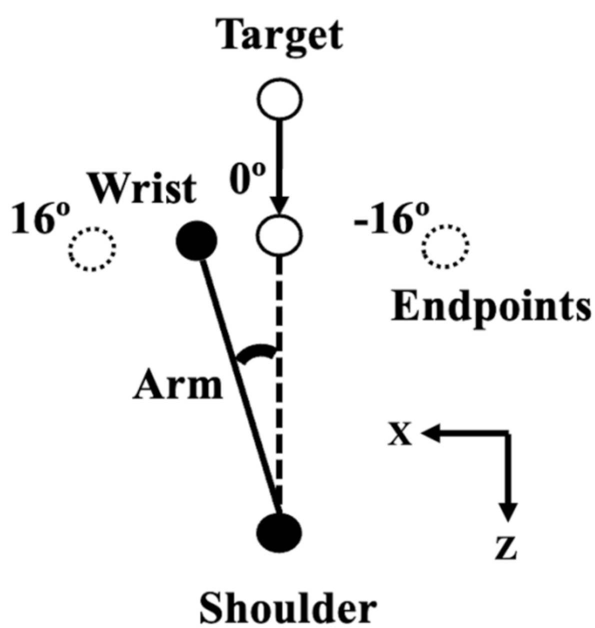


Figure 6.2. Coordinate system and spatial error in VR environment. Spatial error in each trial was angle difference between wrist tracker and target endpoint at a frame where the target reached to its endpoint. Endpoint in each trial was estimated from the participant's shoulder position and tested limb length.

The dynamic reaching test consisted of 30 trials in each of two blocks: accurate vision block (AB) and offset vision block (OB). Within each block, the first 21 trials were adaptation trials, and the last 9 trials were post-adaptation trials (**Figure 6.3**). Visual conditions differed between the blocks only in the adaptation trials, while the post-adaptation trials in each block were all performed with no visual information about the reaching hand position in VR. In AB, the tested hand position displayed in the VR environment was always congruent with the actual hand position in the real-world. In OB, the hand position was medially shifted by 8º with the participant's arm length taken into account. The task involved accurately hitting the moving target with a shoulder elevation movement. The order of target endpoints, block, and tested limb side were randomized across participants.

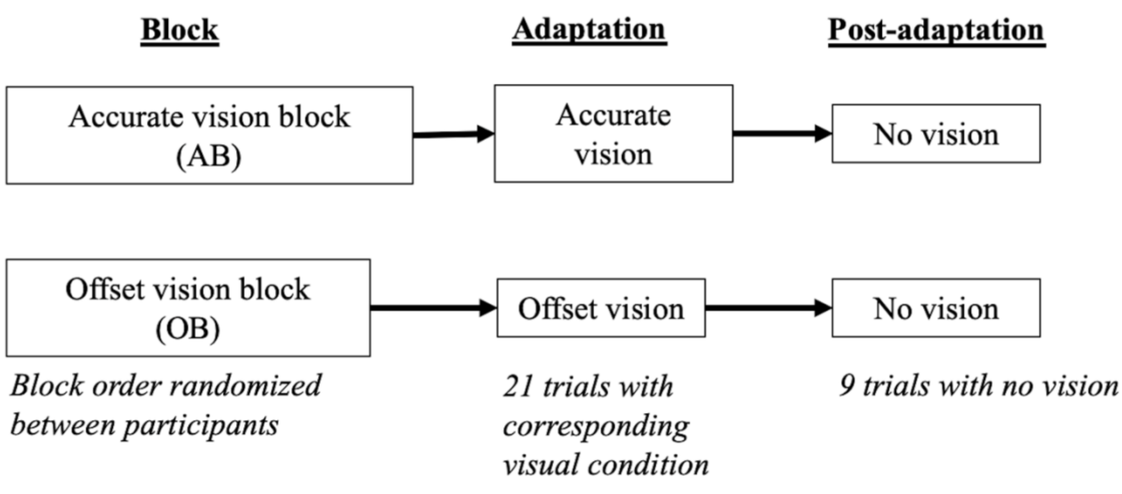


Figure 6.3. Flow of the dynamic reaching test. Visual representation of the reaching hand was projected at the accurate position in AB and was projected at the inaccurate position by 8º in OB_D during adaptation trials. In post-adaptation trials, the virtual hand position was not projected consistently regardless of what block the participant was performing.

2.4. *Data Extraction*

Kinematic data were sampled from the VIVE trackers at 90 Hz and collected using a customized Unity program during the dynamic reaching test. The 3D coordinate system for left hand trials were flipped and adjusted to be consistent with right hand trials. In the dynamic reaching test, hit rate was defined as the percentage of trials in which participants successfully hit the target with their reaching hand for each condition (block x tested limb × target endpoint). This metric was calculated to assess each participant's reaching accuracy. A hit was recorded when the target altered its trajectory as a result of a collision with the participant's visual hand in the VR environment.

The constant spatial error (CSE) were calculated using the **Eq. 6.1** (King et al., 2013).

$$Constant\ Spatial\ Error\ (CSE) = \theta_m = \left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e) \quad \textbf{(Eq. 6.1)}$$

The spatial reaching error, θ_e, was the difference between the wrist tracker position and the target endpoint in degrees. (n) is the number of trials performed within a block and (i) is each trial. CSE defines the mean spatial reaching errors over the trials with directions, either positive or negative with respect to the target endpoint in the horizontal plane (mediolateral) (Morehead et al., 2017; Schroeger et al., 2021). Positive CSE values indicate that the reaching hand landed to the left of the target and negative values indicate it landed to the right, based on our VR environment's coordinate system (**Figure 6.2**). For left arm trials, the coordinate system was mirrored to align with that of the right arm, allowing for direct comparison across arms.

$$Variable\ Spatial\ Error\ (VSE) = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(\theta_e - \theta_m)^2} \quad \textbf{(Eq. 6.2)}$$

θ_m is CSE calculated using **Eq. 6.1**, and VSE defines the consistency of the magnitudes of the repositioning errors around the target angles, rather than the accuracy of the repositioning.

Vision-proprioception reliance score (VPRS) was estimated using **Eq. 6.3** (Spitzley & Karduna, 2022).

$$Vision - Proprioception\ Reliance\ Score\ (VPRS) = -\left(\frac{CSE_{OB} - CSE_{AB}}{8^{o}}\right) \quad \textbf{(Eq. 6.3)}$$

VPRS quantifies the participant's sensory reliance in the zero to one scale. In **Eq. 6.3**, CSE_{OB} is CSE in OB, CSE_{AB} is CSE in AB. A score of 1 indicated that participants placed their arm 8º towards the negative direction in the X axis (to the right) in OB than AB, indicating that participants only used vision as 8º visual offset was seen in OB. A score of 0 indicated that participants placed their arm at the same position in the X axis in both AB and OB, indicating participants only used proprioception.

2.5. *Statistical Analyses*

Four-way ANOVAs were performed for the dynamic reaching errors (hit rate, CSE, VSE, response time, and peak wrist velocity) only in the post-adaptation trials to examine the main effects and interactions of group, limb side, block, and endpoint. Post-hoc pair-wise t-tests with Tukey correction were performed if the reaching errors were found statistically different between the conditions. For VPRS, three-way measures ANOVAs were performed on the last 10 trials of the adaptation trials as well as the post-adaptation trials by excluding the blocks from the independent variables, as VPRS was a ratio of CSE between AB and OB. This provided the data whether the adaptation occurred differently between groups or sides and whether the adaptation effect persisted during post-adaptation trials.

For all the statistical tests, the alpha level was set at 0.05. Effect size η^2 was calculated for each of main effects and interactions in ANOVAs. η^2 of 0.01, 0.06, and 0.14 indicate small, medium, and large effect, respectively (Adams & Conway, 2014). All statistical analyses were performed using R 4.5.0 (R Core Team).

3. Results

3.1. Hit Rate

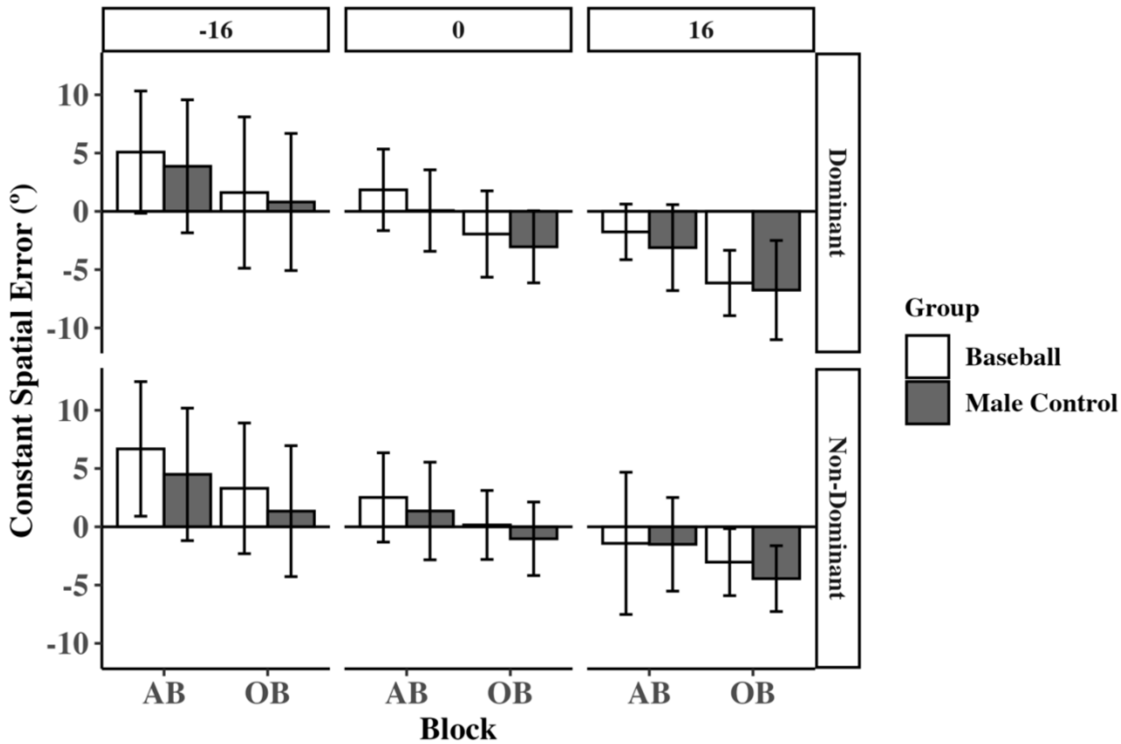
Mean and standard deviations of hit rate (%) in each group were 93.1 ± 20.1 in baseball, 96.5 ± 13.2 in male control, 96.5 ± 14.4 in softball, and 93.4 ± 18.6 in female control. No significant difference in group was found in both baseball-male control comparison and softball-female control comparison ($p = 0.1$ and 0.7, respectively). Main effect of endpoint was found for both group comparisons ($p < 0.001$ for baseball-male control and $p = 0.04$ for softball-female control). In baseball-male control comparison, hit rate was significantly lower at side endpoints (± 16º) than the middle endpoint (0º), while softball-female control comparison showed only +16º endpoint had a lower endpoint than 0º endpoint.

3.2. CSE

For the comparison between the baseball and male control groups (**Figure 6.4**), the mean and standard deviation of CSE in the baseball group were 0.6° ± 5.6°, and in the male control group were −0.7° ± 5.4°. A significant two-way interaction between block and limb side was found ($p = 0.04$), suggesting CSE shifted differently from AB to OB depending on the limb side. CSE shifted negatively by 3.6° from AB to OB on the dominant side while that shift was 2.6° on the non-dominant side, suggesting a stronger influence of the visual offset on the dominant limb.

Main effects revealed a significant difference between groups ($p = 0.046$), where CSEs in baseball athletes biased towards the positive than male controls. The result infers that the reaching hand was positioned more medial with respect to target endpoint in baseball group compared to male control group. Additionally, a significant main effect of endpoint was observed ($p < 0.001$), indicating directional biases across the three endpoints. Post-hoc comparisons showed that CSE at −16° was significantly more positive than at 0° ($p < 0.001$), and CSE at 0° was significantly more positive than at 16° ($p < 0.001$). These findings indicate a consistent medial reaching movement, where male participants tended to reach toward the inner portion of the target. For example, positive CSEs at −16° (lateral endpoint) reflect the hand landing more to the left of the target for right-arm reaches, while negative CSEs at 16° (medial endpoint) reflect the hand positioned more to the right, both consistent with the hand landing on the inner side of the target.

For the comparison between the softball and female control groups, the mean and standard deviation of CSE in the softball group were −1.4° ± 5.5°, and in the female control group were 0.9° ± 7.3°. A significant interaction between group and endpoint was observed ($p < 0.001$), indicating that CSEs differed between groups at certain endpoints. Specifically, female controls exhibited larger errors (far from zero either in positive or negative direction) at −16° and 16°, whereas the CSEs among softball players were less pronounced. Main effects revealed a significant effect of block ($p < 0.001$), with CSEs shifting laterally from 1.3° in AB to −1.8° in OB in response to the visual offset introduced in the medial direction. A significant main effect of limb side was also found ($p < 0.001$), with more positive CSEs on the non-dominant side, suggesting a more pronounced medial reaching bias compared to the dominant side. The same medially biased reaching errors observed in male participants were also seen in female participants. Significant differences in CSEs involving the group were found only in softball-female control comparison.



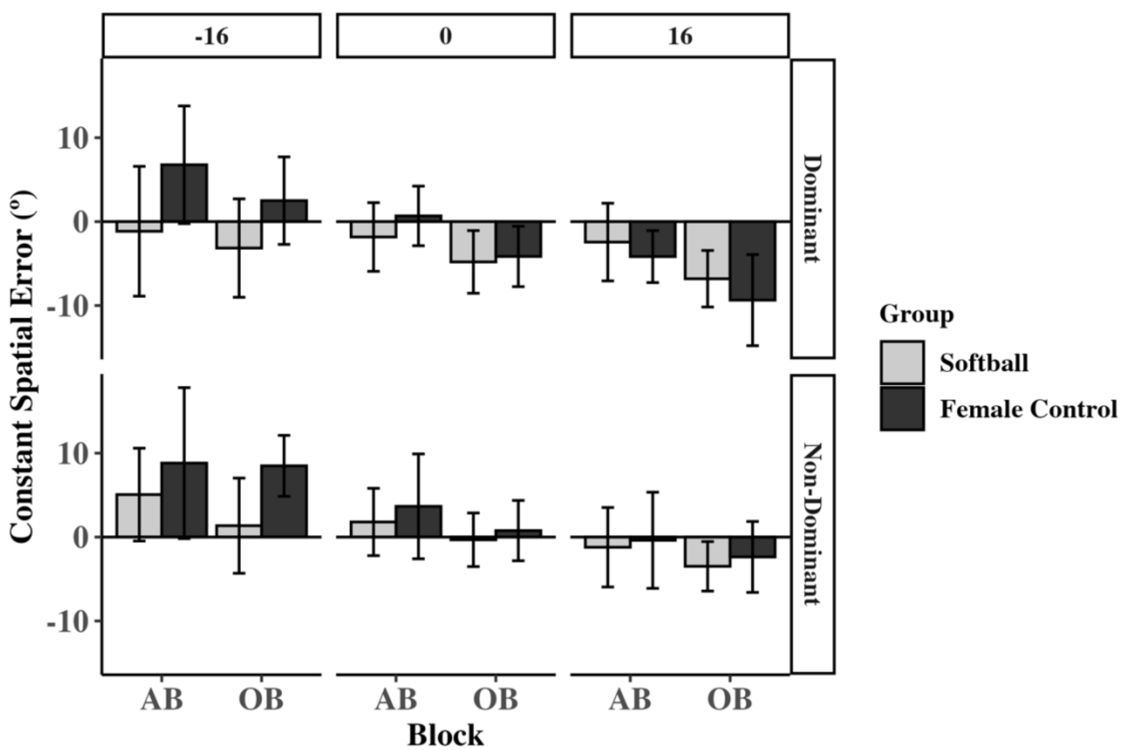
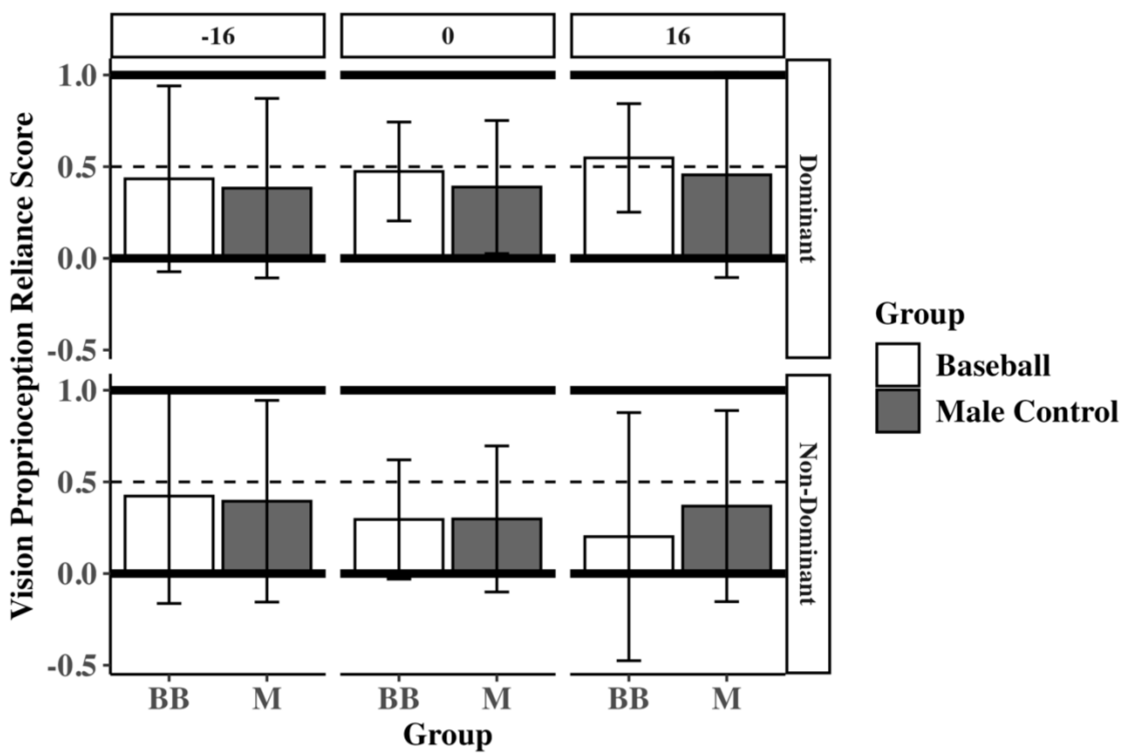


Figure 6.4. Constant spatial error (CSE). Significant group difference was only observed in softball-female control comparison ($p < 0.001$), where the female control group had a larger (more far from zero) CSE at ±16º endpoints than the softball group.

3.3. VPRS

For VPRS, all groups exhibited comparable means and standard deviations (baseball: 0.4 ± 0.5; male control: 0.4 ± 0.5; softball: 0.4 ± 0.5; female control: 0.4 ± 0.7; **Figure 6.5**). A significant main effect of limb side was found in the baseball-male control comparison (p = 0.04), with the dominant limb showing greater reliance on vision (higher VPRS) than the non-dominant limb. No other main effects or interactions reached statistical significance ($p > 0.05$). Individual variability in VPRS was notable across all groups, with some participants showing exceptionally high or low values.



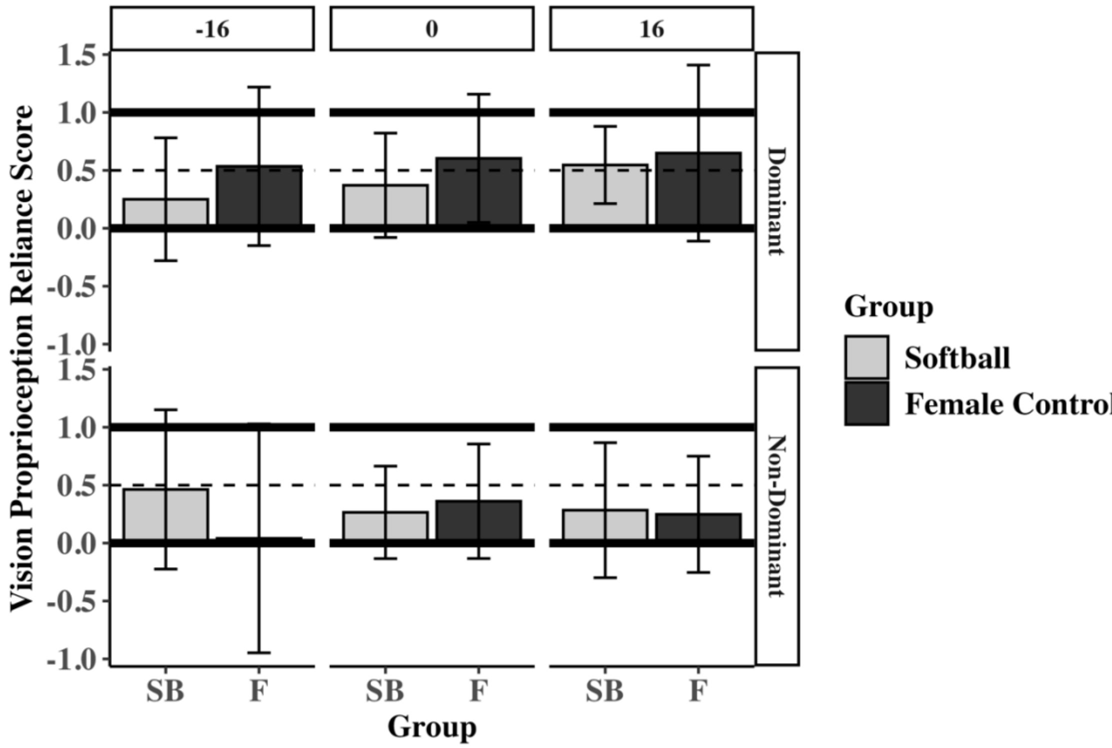
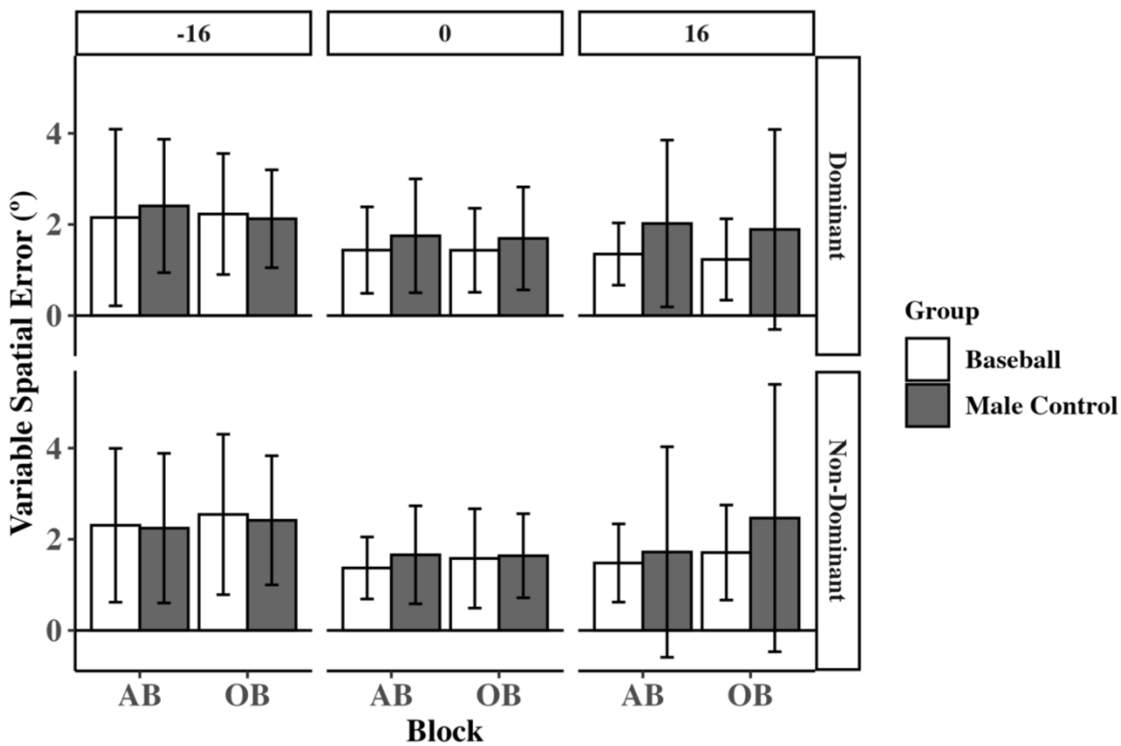


Figure 6.5. Vision-proprioception reliance score (VPRS). No group difference was found ($p > .05$). VPRS was higher in dominant limb in baseball-male control comparison ($p = .04$), indicating male participants (both athletes and non-athletes) relied on vision slightly more in dominant limb reaching than non-dominant.

3.4. VSE

For the comparison between the baseball and male control groups, the mean and standard deviation of VSE in the baseball group were 1.7º ± 1.3º, and in the male control group were 2.0º ± 1.7º. A significant main effect of group was observed ($p = 0.04$), indicating a smaller variability of spatial errors in baseball athletes than male controls. A significant interaction between block and side was found (p = 0.049). Post-hoc comparisons of limb side effects within each block revealed no significant difference between dominant and non-dominant sides in the AB ($p = 0.7$), but a significant difference in the OB, with higher VSE on the non-dominant side ($p = 0.02$). A significant main effect of endpoint was observed ($p < 0.001$), with post-hoc comparisons indicating that VSE at −16° was significantly greater than at 0° ($p < 0.001$) and 16° ($p < 0.001$). The difference between 0° and 16° was not significant ($p = 0.4$).

For the comparison between the softball and female control groups, the mean and standard deviation of VSE in the softball group were 2.2º ± 1.8º, and in the female control group were 2.2º ± 1.6º. No significant main effect of group was observed ($p = 0.8$). A significant main effect of endpoint was found ($p < 0.001$), with greater VSE observed at -16° endpoints compared to the middle endpoint, consistent with baseball-male control analysis. All remaining main effects and interactions were not statistically significant (all $p > 0.05$).


-16
0
16
Dominant
Non-Dominant
Variable Spatial Error (º)
0
2
4
AB
OB
Block
Group
Baseball
Male Control

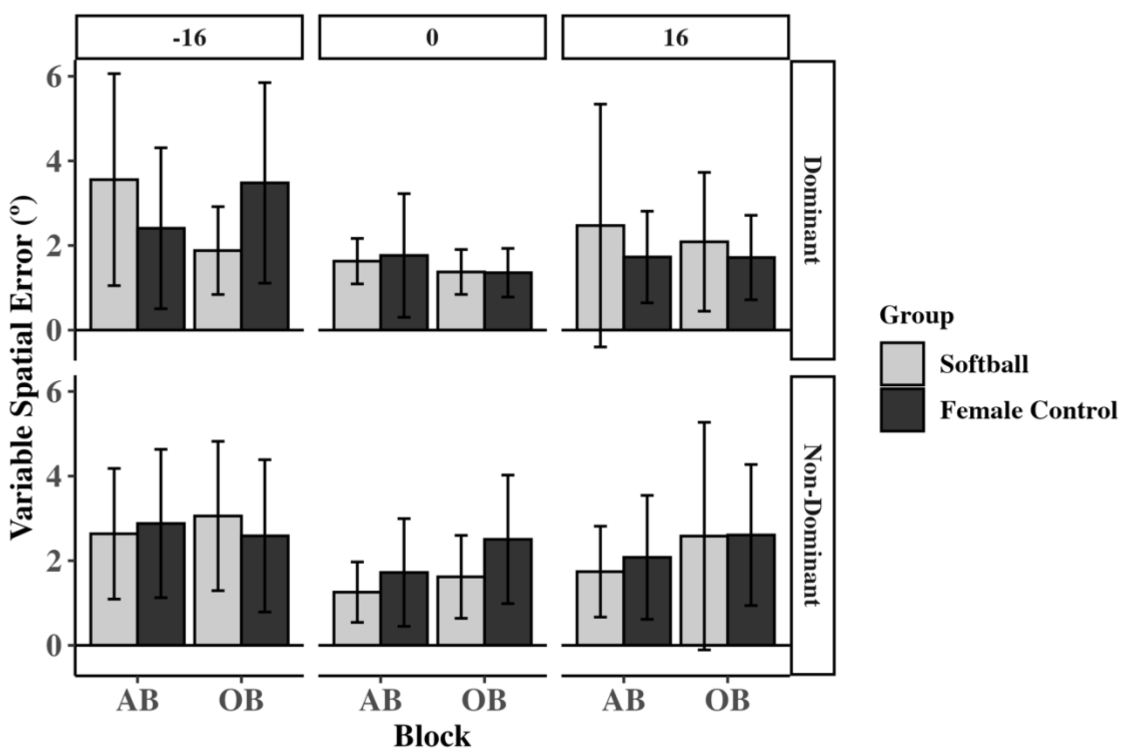
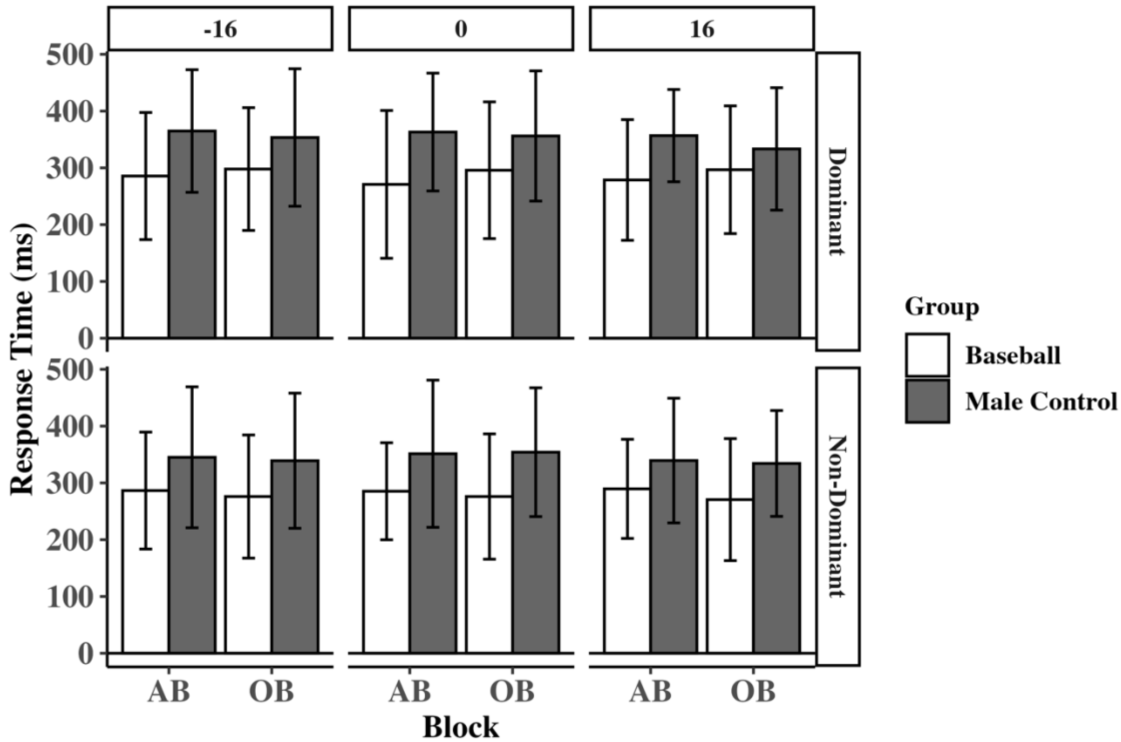

-16
0
16
Dominant
Non-Dominant
Variable Spatial Error (º)
0
2
4
6
AB
OB
Block
Group
Softball
Female Control

Figure 6.6. Variable spatial error (VSE). Baseball athletes had significantly smaller VSE than male controls ($p = 0.04$), while no group difference was found between softball athletes and female controls ($p > 0.05$).

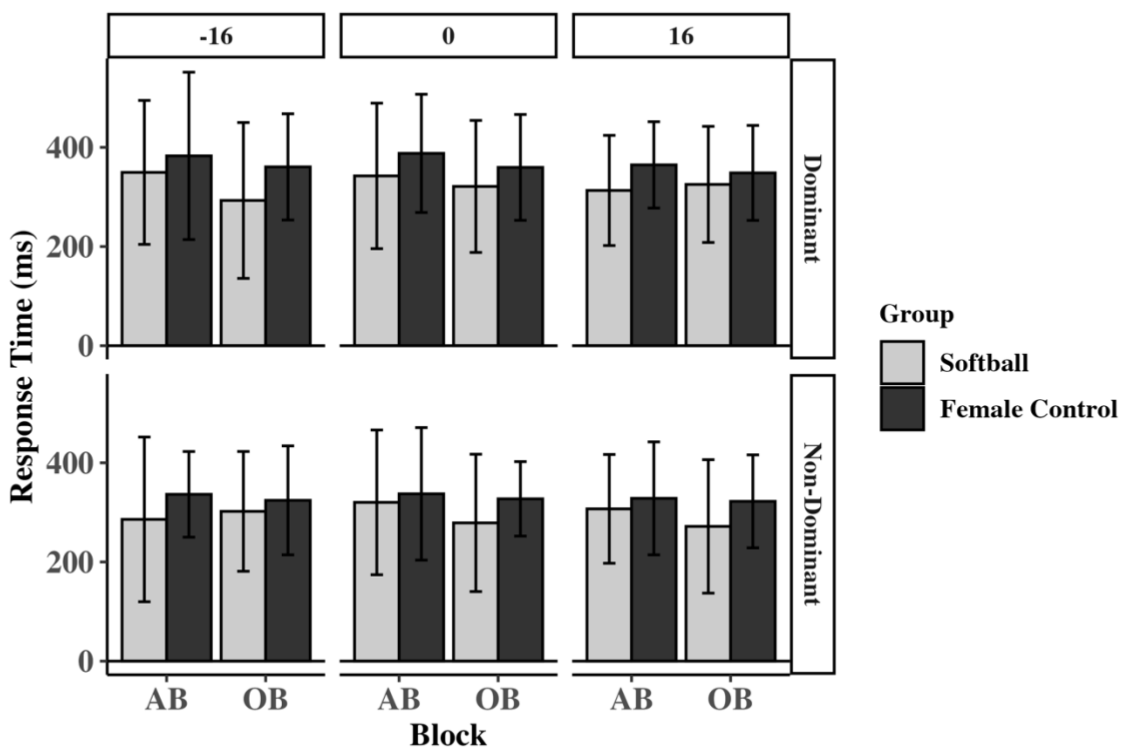
3.5. Response Time

For the comparison between the baseball and male control groups, the mean and standard deviation of response time (ms) in the baseball group were 284.1 ± 107.3, and in the male control group were 349.2 ± 110.3. A significant main effect of group was observed ($p = 0.002$) where significantly smaller (faster) response time was seen in baseball group than male control group. No other significant interactions or main effects were found ($p > 0.05$).

For the comparison between the softball and female control groups, the mean and standard deviation of response time (ms) in the softball group were 309.2 ± 132.8, and in the female control group were 348.3 ± 108.2. No significant interactions or main effects among conditions were found ($p > 0.05$), although softball group had smaller response time than female control group across all conditions at non-significant level.



-16
0
16
Dominant
Non-Dominant
Response Time (ms)
500
400
300
200
100
0
AB
OB
Block
Group
Baseball
Male Control



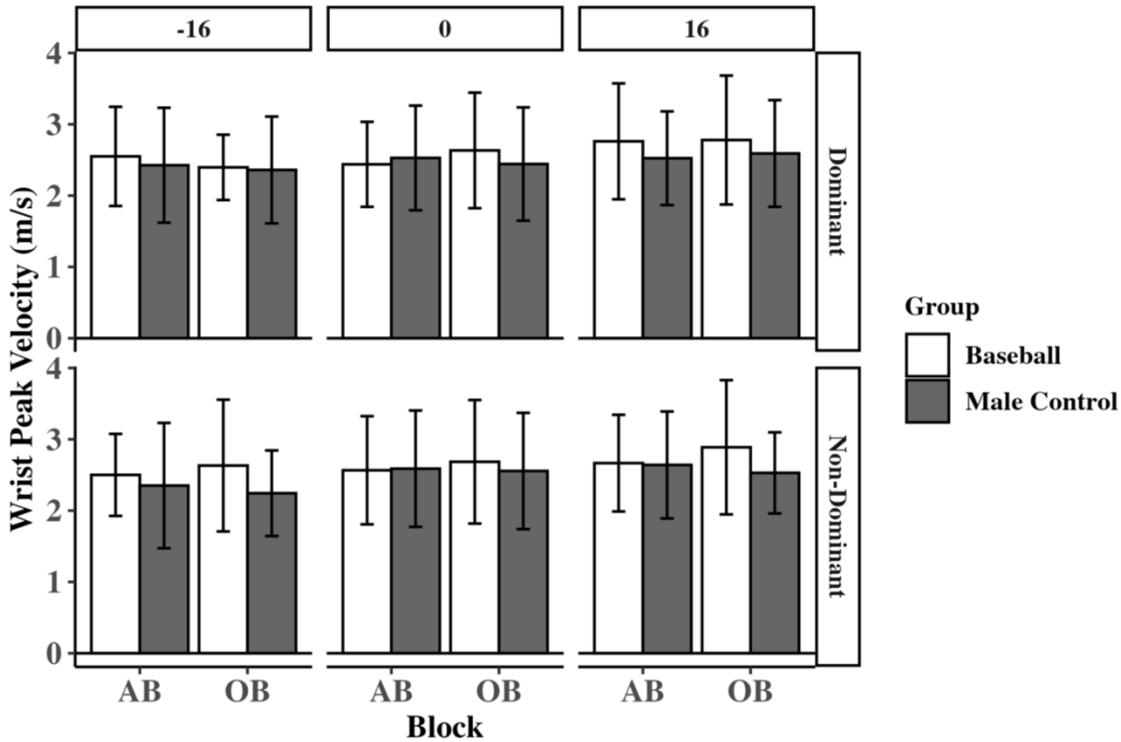
-16
0
16
Dominant
Non-Dominant
Response Time (ms)
400
200
0
AB
OB
Block
Group
Softball
Female Control

Figure 6.7. Response time was faster in baseball athletes than male controls ($p = 0.002$). Softball athletes also showed faster response time than female controls at statistically non-significant level ($p = 0.4$).

3.6. Peak Wrist Velocity

For the comparison between the baseball and male control groups, the mean and standard deviation of peak wrist velocity in the baseball group were 2.6 ± 0.8 meter per second, and in the male control group were 2.5 ± 0.7 meter per second. A significant main effect of endpoint was observed ($p < 0.001$). Post-hoc comparisons indicated that peak velocity at 16° was significantly greater than at −16° ($p < 0.001$) and 0° ($p = 0.02$), and that peak velocity at 0° was also greater than at −16° ($p = 0.01$).

For the comparison between the softball and female control groups, the mean and standard deviation of peak wrist velocity in the softball group were 2.3 ± 0.6 meter per second, and in the female control group were 2.2 ± 0.6 meter per second. A significant main effect of endpoint was also observed ($p < 0.01$), with post hoc comparisons showing significantly higher peak velocity at 16° compared to −16° ($p < 0.0001$) and 0° ($p = 0.003$). In both baseball-male control and softball-female control comparisons, peak wrist velocity was the fastest when reaching for 16º (medial) endpoint.


-16
0
16
Dominant
Non-Dominant
Wrist Peak Velocity (m/s)
AB
OB
Block
Group
Baseball
Male Control

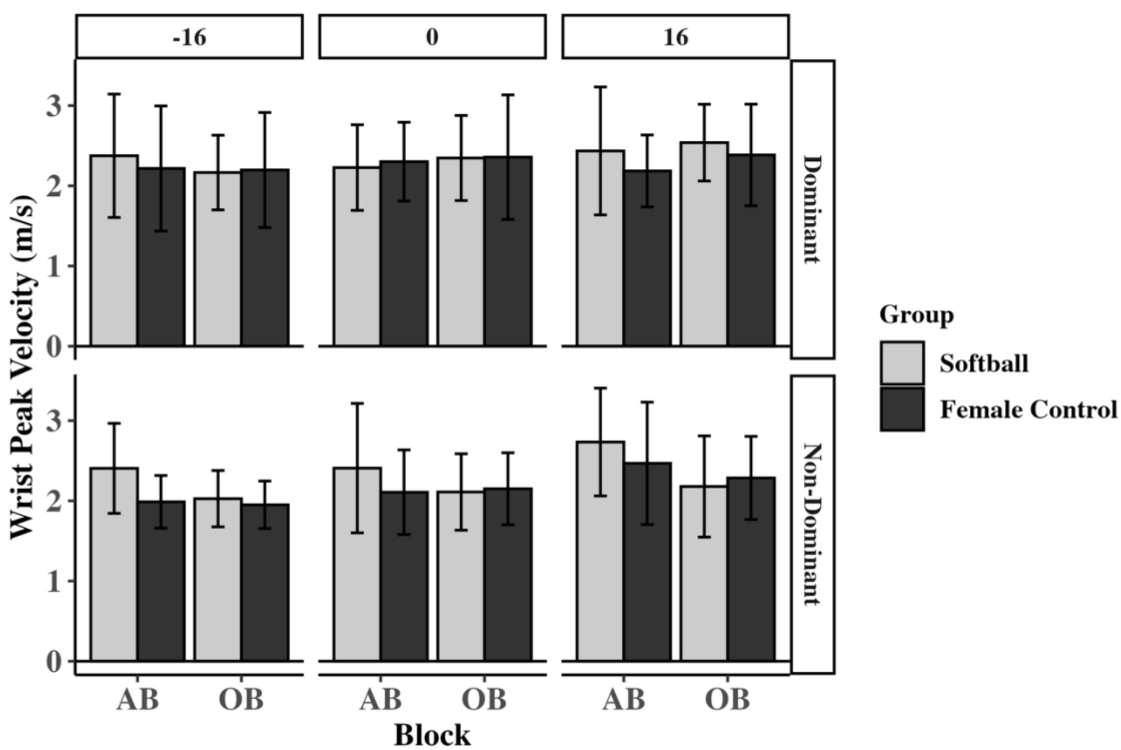
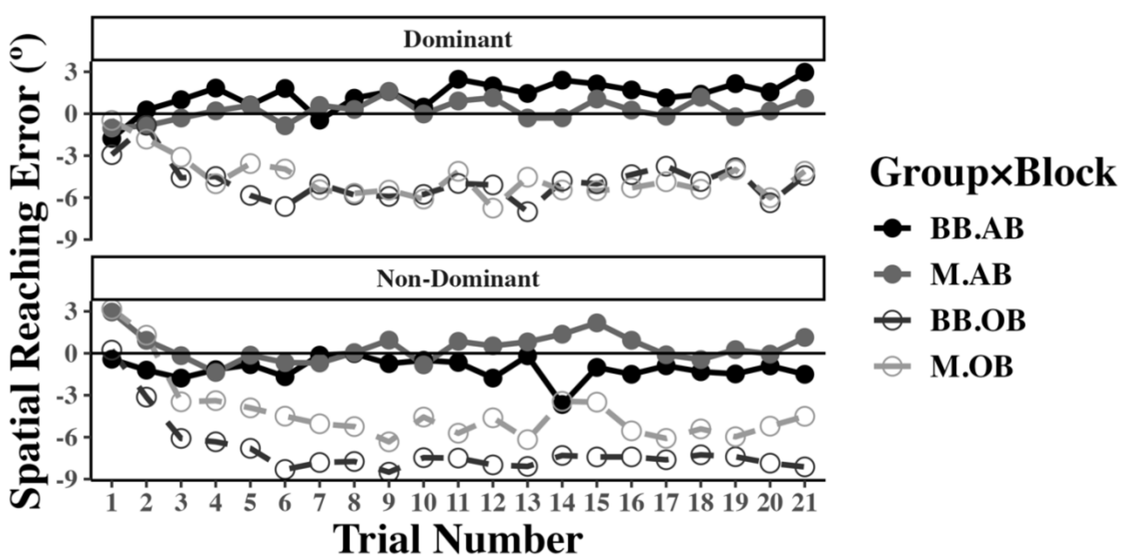

-16
0
16
Dominant
Non-Dominant
Wrist Peak Velocity (m/s)
AB
OB
Block
Group
Softball
Female Control

Figure 6.8. Peak resultant linear wrist velocity (m/s). No group difference was found ($p > 0.05$), while the peak wrist velocity was faster when reaching for side endpoints (±16º) than the middle endpoint (0º) ($p < 0.02$).

3.7. Adaptation Trials

In **Figure 6.**, changes in spatial reaching error during the twenty-one adaptation trials in each group and limb are summarized. VPRSs from the last ten adaptation trials are also provided in **Figure 6.**. Although statistic tests were not performed, the data visualized in the figures ensures that spatial reaching error trended differently between AB and OB. The results indicate that different adaptation patterns have occurred between the two visual conditions before the participants started post-adaptation trials without vision of their reaching hand. In both limbs and groups (baseball, male control, softball, and female control), VPRS exceeded over 0.5 across all conditions, indicating that participants relied more on visual hand than their perceived hand position from proprioception that are different from the post-adaptation trials (**Figure 6.**).



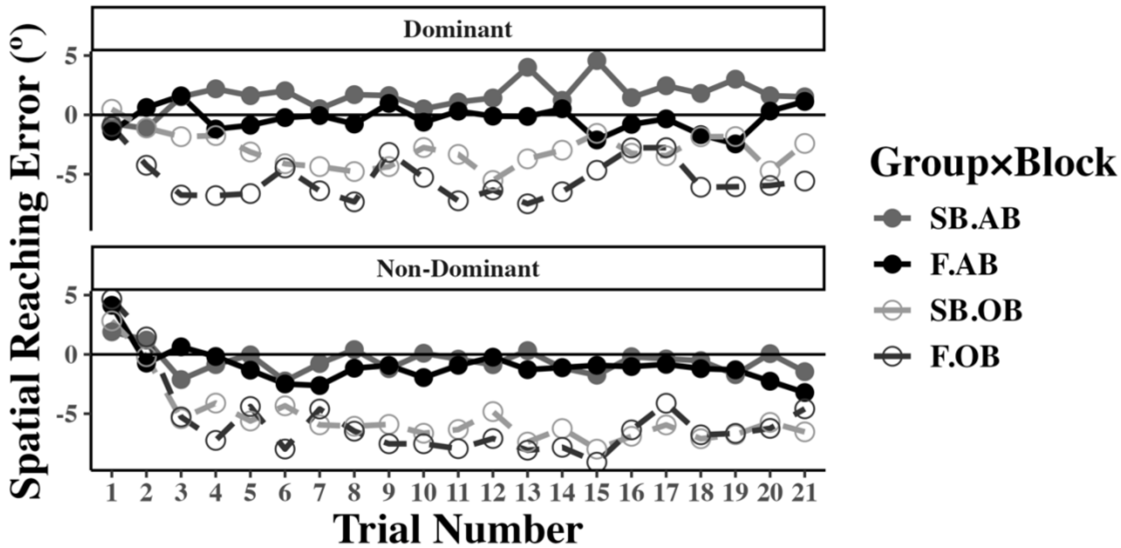


Figure 6.9. Spatial reaching errors in each adaptation trial 1-21. Top: baseball/male control group. Bottom: softball/female control group.

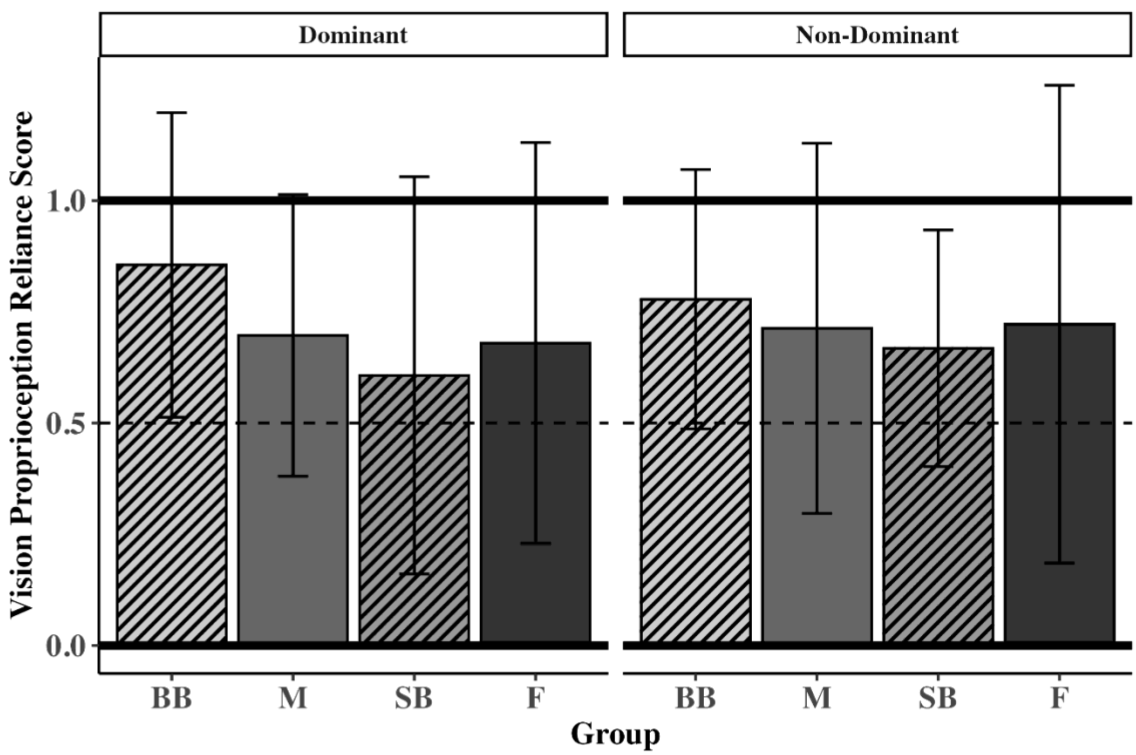


Figure 6.10. Vision-Proprioception Reliance Score (VPRS) from the last 10 trials of adaptation trials. It was above 0.5 in all groups, indicating visual offset caused some changes in the reaching hand endpoint for all groups.

4. Discussion

The current study investigated differences in motor control patterns in upper limb reaching movements in baseball/softball athletes and non-athletes. The hypotheses in the current study were partially supported as differences between the athletes and non-athletes were observed in some of the spatial and temporal variables. Hit rate was not significantly different between the athletes and non-athletes, which suggests that reaching accuracy in the dynamic reaching test was comparable among groups.

For CSE, the only condition involving group differences was between softball athletes and female controls when reaching for medial and lateral endpoints. Hit rates were lower across all groups at these endpoints, suggesting increased difficulty when the target moved to medial or lateral endpoints. Softball athletes likely maintained their reaching accuracy at these endpoints due to their greater experience in catching softballs thrown or hit toward them compared to female controls. However, this pattern was not observed in the baseball versus male control comparison, possibly due to differences in their sport experiences. In the self-reported sport experience questionnaire included in this study, more male control participants indicated experience in sports involving unilateral ball catching, such as basketball and water polo, compared to female control participants. Conversely, soccer and running, which do not typically involve arm reaching, were the most common sports among female controls. Previous literature suggests males may possess better motor control for ball-catching tasks due to differences in brain function (McGivern et al., 2012). Females reportedly rely more on the ventral stream responsible for object recognition (e.g., shape and color), whereas males depend more on the dorsal stream, specialized in analyzing object movement (e.g., velocity and direction) (Goodale & Milner, 1992). However, softball athletes in this study may have enhanced their motor control capabilities beyond typical female controls through extensive training in ball catching and hitting. Baseball athletes might also exhibit better motor control compared to male controls, however, the dynamic reaching test in the current study may not have been sufficiently challenging to highlight these differences. Previous research indicates task difficulty can influence the outcomes of arm-reaching tests (McGivern et al., 2012; Schroeger et al., 2021).

VPRS indicates relative reliance between vision and proprioception by calculating the ratio of CSEs between visual conditions (AB and OB). There was no significant difference among the groups, though proprioception was slightly more relied on in the non-dominant limb compared to the dominant limb across all groups. These results do not support our hypothesis, which predicted higher reliance on proprioception in the non-dominant arm only in athlete groups. Baseball and softball athletes were expected to exhibit greater reliance on proprioception in their non-dominant (glove side) limb due to extensive ball-catching experiences, allowing them to perform catching-like movements without heavily relying on vision in the current experiments. Instead, the results suggest that higher reliance on proprioception in the non-dominant arm is not athlete-specific but rather reflects fundamental motor control patterns commonly observed in physically healthy young individuals. Previous research has indicated that proprioception is more accurate in the left arm because the right hemisphere of the brain predominantly manages proprioceptive signal processing, with efferent motor signals from the brain executed to contralateral limbs (Mickevičienė et al., 2011; Strong et al., 2023). Since over 85% of participants in this study were right-hand throwers (80 right-handed vs. 16 left-handed across all groups), most non-dominant arm reaching trials involved the left arm. An interesting finding from the current study is that participants appeared to rely more on proprioception in their non-dominant limb even when vision was provided, rather than performing accurately in their non-dominant limb under proprioception-only conditions without vision as observed in prior research (Goble & Brown, 2008; Schmidt et al., 2013; Strong et al., 2023). This aligns with multisensory optimization theory, which proposes that sensory signal reliance depends on the quality and availability of those signals (Block & Bastian, 2011a). Participants likely relied more on proprioception in left arm reaching because their body, either at the CNS or peripheral limbs, recognized enhanced proprioception quality compared to the right arm.

Unlike CSE, VSE differed only between the baseball and male control groups, while no differences were observed between softball and female control groups. VSE measures reaching consistency across trials rather than accuracy and was assessed during post-adaptation trials without visual feedback about hand position. Baseball athletes demonstrated greater consistency in spatial reaching error compared to male controls in this context. VSE reflects the amount of noise in the CNS, which typically increases with greater visual uncertainty (Goble & Brown, 2008; Sarlegna & Mutha, 2015). Examples of such uncertainty include when reaching targets disappear, appear blurry, or are small in size. The observed group difference in VSE suggests that baseball athletes had lower noise in their motor system and greater certainty in their reaching movements compared to male controls. Similar to the smaller CSE observed in softball athletes compared to female controls, extensive experience in reaching for dynamically moving balls likely enhanced baseball athletes' ability to process visual input and execute arm movements with reduced noise, even under conditions of uncertainty and lack of visual hand position feedback, despite having adaptation trials with vision prior to the post-adaptation phase. However, the absence of group differences in VSE between softball and female controls could be attributed to the small sample size (n = 11 per group) and varied playing levels within the softball group, which included one Division I player, eight NAIA players, and two club-level players. Interestingly, softball players exhibited CSE values closer to zero than female controls, while their VSE levels remained comparable to their counterparts.

Response time was consistently faster in athlete groups compared to their respective control groups, whereas peak wrist velocity, another temporal measure, showed no significant differences among groups. The faster response time observed in the athlete groups aligns with previous research findings (Kida et al., 2005; Yamashiro et al., 2013), which also demonstrated quicker reaction times in baseball players compared to controls. Additionally, these studies identified quicker reaction times and somatosensory processing in baseball athletes compared to track athletes through electroencephalogram analysis during finger-tapping tasks. Baseball and softball require rapid responses for successful catching or hitting, with hitting demanding precise bat movements to contact the ball within approximately 0.4 seconds after its release from the pitcher. This intensive training likely enhanced athletes' visual processing speed, contributing to their quicker response times. Peak wrist velocity was slightly but consistently higher in the athlete groups compared to the control groups at statistically non-significant level in the current study. While previous research suggested a potential trade-off between hand velocity and reaching accuracy (Xiao et al., 2019), the athletes in this study did not exhibit such a trade-off. They achieved faster response times and greater wrist velocity without compromising spatial accuracy as indicated by hit rate, CSE and VSE. Overall, combining spatial and temporal reaching outcomes, baseball and softball athletes displayed somewhat unique motor control patterns compared to age-, sex-, and throwing hand-matched controls.

Although some notable group differences emerged in spatial and temporal variables, these differences were not as pronounced or consistent between baseball and softball athletes as hypothesized. Notably, most significant main effects and interactions involved target endpoint, suggesting motor control differences appeared more prominently when reaching toward medial and lateral (±16º) targets. This observation may relate to task difficulty, as hit rates were significantly lower at these lateral endpoints, and these endpoints showed significantly larger CSE and VSE than the middle endpoint (0º). Researchers should carefully set task difficulty depending on their research questions, as the task that is too easy or difficult could mask unique motor control patterns of individuals. Controlling task difficulty by changing target's velocity, trajectories, or even making targets occluded could influence reaching performance significantly. To contextualize the current task difficulty, the target took about one second to reach endpoints, moving from 5 meters away at 5 m/s. In comparison, a baseball pitched at 90 mph reaches the catcher in less than 0.4 seconds. Thus, the dynamic reaching task in this study was relatively easy, especially compared to more complex tasks such as baseball or softball hitting.

Limitations of the current study includes the sample size in the softball-female control comparison, as only 11 participants in each group were recruited compared to 37 participants per group in baseball-male control comparison. Furthermore, the softball group consisted of the players from multiple playing levels including NCAA Division I, NAIA, and club softball. Relatively small sample size with varying softball playing levels may have influenced some of the results that were different from the baseball-male control comparison. The reaching target was a baseball size sphere to resemble ball catching situations in baseball while softballs are much bigger than baseballs. For the softball athletes, the current experiment may not accurately represent their ball catching situations in softball and previous studies suggest that the motor control develops specific to situations including target size (Proteau & Isabelle, 2002; Reichenthal et al., 2016). Lastly, this experiment did not include a no vision block where only proprioception is available without projecting a visual hand during adaptation trials due to time restriction that we were able to take for each participant to perform the experiments. No vision condition would have provided the fundamental proprioceptive accuracy between the athletes and non-athletes on both sides of the limbs.

In conclusion, the current study examined motor control patterns on dominant and non-dominant arm of baseball and softball athletes compared to their control participants. The athletes exhibited superior reaching accuracy in a few variables (CSE and VSE) with significantly faster response time while results in these reaching errors were not consistent between baseball-male control and softball-female control comparisons. Task difficulty may be a factor that future studies need to consider carefully as the current study had more pronounced differences in reaching performance in trials with greater difficulty (side endpoints).

CHAPTER VII

CONCLUDING SUMMARY

1. Summary of Results and Findings

This dissertation aims to understand sensory integration mechanisms for upper limb movements in a VR environment, with a focus on effect of intention, population, and limb side. The recent advancement of VR technologies has significantly widened the scope of motor control research, as the currently available VR systems enable researchers to design upper limb reaching tasks in a 3D environment and answer research questions that were difficult to investigate previously. Since motor control patterns change and adapt specific to given situations, it is important to understand whether movement intention and population/limb-specific movement patterns appear in different types of reaching movements that we perform in daily life.

The body of work presented in this dissertation contributes to that understanding in several keyways. First, it examines whether vision dominates proprioception in a joint repositioning task (static reaching test) and whether a conscious effort to ignore vision could increase relative reliance on proprioception. Second, it explores whether the dominance of vision remains in a dynamic reaching task where a reaching target is moving toward participants rather than fixed at a certain location. Lastly, it examines population and limb-side differences in sensory integration patterns in both static and dynamic reaching tests. As a whole, the studies outlined in this dissertation contribute to the broader base of motor control, offering insights into situation-specific motor control and adaptation patterns, including the effect of movement intention, type of movement (joint repositioning vs. ball catching), side of the upper limbs, and population (male vs. female, athlete vs. non-athlete). The sections below provide an overview of the main outcomes from each topic area.

1.1. Movement Intention

Chapter II of this dissertation provides evidence that vision is a dominant sense relied on to perform the active shoulder JPS test in VR, while humans may be able to ignore it and rely more on proprioception through conscious effort. In the offset vision block with the intention to ignore vision, participants were able to downscale their relative reliance on vision from 0.8 to 0.5 in the vision-proprioception reliance score. Reduction in the constant error and the vision-proprioception reliance score suggests that participants reduced their reliance on vision by about 40% when they tried to ignore it. Interestingly, they were not able to completely shut down the visual input and still integrated vision, as the reliance score remained at 0.5, indicating equal reliance on vision and proprioception.

1.2. Types of Movement

Chapter III of this dissertation explored changes in sensory reliance in two different upper limb tasks, JPS and the dynamic reaching test. The dynamic reaching test was developed to better understand whether sensory reliance differs depending on the type of movement. JPS served as a benchmark test, and VPRS was compared between the two tests. It was found that VPRS was lower in the dynamic reaching test than in JPS, potentially because vision was used to track a target approaching the participants, while proprioception played the main role in tracking where the reaching hand was at a given moment and guiding it to the interception point. This was an exploratory study to further understand the role of vision and proprioception in ball-catching-like movements, and baseball and softball athletes were recruited for the studies in the following chapters.

1.3. Population Difference

Chapters IV through VI of this dissertation focused on population differences in sensory integration mechanisms by recruiting baseball and softball athletes, as well as female and male non-athletes. Both sides of the upper limbs across different populations were tested in JPS and the dynamic reaching test used in the prior chapters. Male non-athletes were found to have better spatial reaching accuracy without a significant difference in relative reliance on vision and proprioception compared to female non-athletes. Baseball and softball athletes also showed better spatial reaching accuracy or consistency without differences in VPRS compared to their sex-matched control groups. Response time was also faster in the athlete groups than in the control groups. These results suggest that motor control patterns may differ due to differences in sex and long term ball-catching and hitting experiences, which require very quick and accurate upper limb reaching movements.

Interestingly, the non-dominant limb (mostly the left arm for most participants in the current study) showed better response time with greater reliance on proprioception compared to the dominant limb, regardless of population. These results suggest the inherent advantage of the left arm for reaching movements, potentially because the right hemisphere of the brain predominantly functions to process sensory inputs and execute reaching movements, and the left arm receives signals from the right hemisphere.

2. Recommendations for Future Work

Vision and proprioception are the primary senses involved in planning and executing upper limb reaching movements. However, motor control is specific to each situation, and relative reliance on vision and proprioception can be optimally adjusted, according to optimal integration theory. While the JPS test can be used to quantify how much individuals depend on vision and proprioception in joint repositioning movements, it may not be sufficient to understand how baseball and softball athletes integrate these sensory inputs in their CNS and execute quick and accurate upper limb movements to catch or hit the ball. This work examined the sensory integration and movement execution of athletes compared to non-athlete controls using the HTC VIVE VR system, which offers an immersive 3D environment resembling the ball-catching situations that athletes experience on the field.

Future work is encouraged to take advantage of VR systems to further examine sensory integration mechanisms in different populations under various conditions. VR technologies could be a strong tool for training or rehabilitation, as they offer a more engaging and realistic environment for those who need to learn or recover body movements. Patients recovering from stroke could use VR to restore upper limb functions, such as picking up a mug of coffee—movements that become very safe if patients perform them using a "virtual mug" to practice. Nowadays, baseball athletes use VR systems to practice their hitting skills, as they can project realistic pitcher throws in a virtual field. However, very limited amount of research has been done to identify the effect of VR training and rehabilitation.

Dynamic reaching tests could be modified in a variety of ways depending on the research questions. Eye-tracking function is another feature that the HTC VIVE offers, but it was not integrated in the current work. Given that the influence of vision differed depending on movement intention, type of movement, and limb side, future studies are encouraged to examine whether gaze point or saccades (rapid eye movements) change in these situations or protocols. Additionally, the task difficulty of the dynamic reaching test can be controlled using target velocity, trajectory, and occlusion. These variables were consistent within the current work, but it would be interesting to see how task difficulty, modified by these variables, influences sensory integration mechanisms and reaching performance.

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