NORTHWESTERN UNIVERSITY

Gaze and Gait: How Motor Learning and Concussive Injury Change Where We Look and Our Visual Reliance

A DISSERTATION

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Abstract

Visual information plays a critical role in controlling movement. People use visual information to plan future actions and correct current actions through feedforward and feedback processes, respectively. We can gain insights into these visually guided motor control processes by quantifying where people look during movement and measuring how much they rely on different pieces of visual information. Researchers have established that the visual information people collect and their reliance on the collected information changes based on their surrounding environment and capacity to move (e.g., motor skill level or injury). My thesis expands on this knowledge by examining how where-we-look (i.e., fixation distance) and visual reliance changes throughout the motor learning process; first with an online motor learning task and then with practice of a precision stepping task. My research clearly demonstrates that fixation distance increases with practice. In contrast, changes in visual reliance are dependent on the task being performed. Additionally, my research suggests that changes in visual reliance are a consequence of changing motor skill. I then apply this approach to examine whether individuals who have recently been medically cleared from a concussion exhibit altered collection of and reliance upon visual information (gaze behavior). While my research does not find significant visual changes during walking following the concussion, it does find persistent postural balance and oculomotor deficits. Together, these results provide new information about how gaze behavior changes with motor learning and following a concussion. Outcomes from this dissertation may be valuable for informing gaze-based intervention practices and for further exploring why individuals post-concussion exhibit persistent gait deficits.

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Preface

Chapter 3: A preprint of this work is available at: https://osf.io/a3bkx/

Chapter 4: This work has been published in the Journal of Neurophysiology (Cates and Gordon 2022).

Chapter 5: A preprint of this work is available at: https://osf.io/659cr/

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Chapter 1: A *Walk* through what you will *see* in this dissertation

“Hey, watch where you step!” We have all heard and said this phrase while navigating our world. Given the ubiquitousness of the phrase, it is no surprise that vision plays a major role in how we plan and execute our movements. While research suggests that the type of vision we collect and how we use vision changes based on our motor ability, how and whether vision changes during the motor learning process is not understood. My dissertation therefore explores the role of vision in motor learning through multiple tasks and populations. In Chapter 2, I provide background knowledge of what the role of vision is in controlling movement, and how that role changes based on the individual’s abilities and/or the environment. In Chapter 3, I present evidence about the role of vision during motor learning of an online typing task. Chapters 4 and 5 investigate the role of vision during a locomotor learning task, with Chapter 4 focusing on where people look and Chapter 5 focusing on how people rely on vision to perform the task. Chapter 6 applies the knowledge gained in the previous chapters to explore the role of vision during walking among individuals post-concussion. In Chapter 7, I establish some common themes about how fixation distance and visual reliance change with motor learning. Finally in Chapter 8, I conclude by discussing alternative perspectives, clinical implications, and outstanding questions.

General Outline and Summary of Experiments

Below I provide an overview of the organization of the dissertation and the aim, topic, and takeaway of each chapter.

Chapter 2: What alters gaze behavior?

I provide background literature and establish how different tasks and individual characteristics affect fixation distance and visual reliance. I examine how 6 different factors affect gaze behavior; specifically, terrain, age, neurologic disorders, confidence/anxiety, elite athleticism, and after motor learning; and visualize gaze behavior differences of these factors compared to healthy young adults walking on flat ground. Finally, I discuss the gaps in our knowledge of how gaze behavior is affected throughout the motor learning process and following a concussion.

Chapter 3: Motor Learning alters vision, but vision does not alter motor learning

Aim 1: To determine how gaze behavior changes during finger coordination learning.

I present the results of two experiments that used an online typing game to assess how visual availability affected motor learning (Experiment 1) and how motor learning affected performance with limited visual information (Experiment 2). The online typing game consisted of targets dropping from the top of the game screen with participants responding when the targets crossed a designated location on the bottom of the screen. In Experiment 1, 52 participants practiced the task in one of three conditions: Full vision; No feedback (when the targets were not visible on the lower half of the game screen), No feedforward (when the targets were not visible on the upper half of the game screen). In Experiment 2, visual reliance was assessed for 145 participants before and after a full vision training period. Visual reliance was defined as the decrease in performance between a full vision condition and a limited vision condition (no feedback or no feedforward).

Hypothesis 1: Limiting visual information during training will reduce overall motor learning.

Contrary to my hypothesis, limiting visual information did not alter motor learning, only immediate performance. Participants were less accurate during the limited vision conditions, but neither the rate of improvement (a measure of motor learning) nor post-training performance (when all participants performed the task with full vision) were limited by training condition.

Hypothesis 2: Following training, participants will alter their visual reliance to emphasize feedforward visual information more and feedback visual information less.

In partial support of my hypothesis, I found that practice reduced participant reliance on vision altogether, rather than increasing feedforward reliance and reducing feedback reliance. People became more visually flexible with training, defined as being better able to use whatever visual information was available to them to complete the task.

Taken together, the results of the two experiments suggest that motor learning affects gaze behavior, but constraining gaze behavior does not affect motor learning.

Chapter 4: Don't watch your step: Gaze behavior adapts with practice of a target stepping task.

Aim 2A. To determine how gaze behavior changes during locomotor learning

I present the results of an experiment on how locomotor learning affects where people look during a target stepping task. Twelve people walked on a treadmill while stepping targets were projected onto the treadmill surface. Participants practiced accurately stepping on the targets and received auditory feedback to inform and help update their performance.

Hypothesis: With practice of a precision stepping task, people will decrease their step error and increase their fixation distance.

As hypothesized, people did decrease their step error (the distance between the foot and the target) and increase their fixation distance (how far ahead they fixated) with practice. There was also evidence of a consolidation effect, as most of the changes in step error and fixation distance occurred between trial blocks rather than from step to step within trial blocks.

Chapter 5: Seeing does not mean processing: Where we look and the visual information we rely on change independently as we learn a novel walking task

Aim 2B. To determine how gaze behavior changes with locomotor learning

I examined how participant visual reliance, a measure of visual processing rather than the visual sampling previously explored, changes with locomotor practice. Twenty people walked on a treadmill while completing a precision stepping task. Visual reliance was repeatedly probed through the use of limited visual conditions: 1) No feedback condition (hiding targets less than 1.5 steps ahead) and 2) No feedforward condition (hiding targets greater than 1.5 steps ahead). Visual reliance was defined as the decrease in stepping performance between a limited and full vision condition. Participants completed sets of three training trials with full vision in between probe periods (one block of each visual condition) to create the locomotor learning conditions.

Hypothesis: With practice, people will become more reliant on feedforward visual information and less reliant on feedback visual information

Counter to my hypothesis, people became more reliant on feedback visual information with practice, while their reliance on feedforward visual information was unchanged. Contrary to the results of Chapter 3 (where visual reliance decreased with practice), this finding suggests that the task being learned affects how visual reliance changes with practice. The results did support the findings of Chapter 4, with people looking farther ahead with practice. When combined with the increase in feedback visual reliance, the results suggest people use visual information differently as they practice the precision stepping task, such as more efficient visual processing or by shifting to using peripheral vision more as they practice the precision stepping task.

Chapter 6: Gaze behavior during walking is unaffected after recovery from a concussion

Aim 3: to determine how gaze behavior changes following a concussion

To understand why people exhibit persistent gait deficits following medical clearance from a concussion, I examined whether gaze behavior is similarly altered during walking after a concussion. Twelve people who were recently medically cleared from a concussion and twelve matched controls completed a series of tasks to assess their fixation distance, visual reliance, and locomotor learning during walking. Using the precision stepping tasks described in Chapters 4 and 5, I assessed if individuals who recently recovered from a concussion exhibit altered gaze behavior during walking.

Hypothesis: People who recently recovered from a concussion will exhibit altered gaze behavior, specifically fixating closer to themselves and displaying an increased reliance on feedback visual information.

Contrary to my hypothesis, I did not find any evidence of altered gaze behavior during walking. People post-concussion exhibited similar fixation distances to their matched controls, along with similar visual reliance on both feedback and feedforward visual information. While further study is needed, it is likely that the persistent gait deficits following a concussion are not related to disruptions in gaze behavior.

Chapter 7: A meta-view of gaze behavior changes

Chapter 7 takes a meta-analytical approach to aggregate and compare the results of the four studies presented in this dissertation. I find that fixation distance consistently increases with locomotor learning, while changes in visual reliance depend on the task and the individual. I discuss how differences in task design and study participants across the different studies may have affected changes in gaze behavior.

Chapter 8: Conclusions, clinical implications, and future directions

I conclude the dissertation with a summary of the research presented and discussing alternative explanations and frameworks. I discuss the clinical implications of the knowledge gained and present outstanding questions raised by the research, including how future studies research could answer these questions.

Chapter 2: What Alters Gaze Behavior?

Gaze behavior captures a combination of where people look and how people utilize visual information to perform a task. The present chapter will start by describing the gaze behavior of healthy young adults. I then present six different situations, relating to either the individual or the environment, which alter gaze behavior when compared to healthy young adults. These situations set up the basis for the dissertation, exploring how the use of vision differs depending on the situation presented. The chapter ends with a description of the current gaps in the literature, including how the present dissertation may provide novel insights into how gaze behavior changes with motor learning and post-concussion.

The Gaze Behavior of a Healthy Young Adult

As mentioned, gaze behavior categorizes where people look and how they use visual information to perform a task. People exhibit a variety of different gaze behaviors based on a wide range of factors. Here, I focus on walking and the gaze behaviors associated with planning and executing a gait pattern which ensures safe and efficient locomotion.

Visuo-locomotor Control Systems: Feedback vs Feedforward

People make a range of visual fixations during locomotion which inform both a feedforward and a feedback visuo-locomotor control system (Marigold 2008, Matthis et al. 2018, Patla 2003). Feedforward visual information is information relating to future steps and is particularly important for detecting potential hazards along an individual’s path (Marigold 2008). Feedforward visual information creates open-loop motor plans which are necessary during walking for both accurate foot placement (Hollands and Marple-Horvat 1996) and clearing an obstacle (Patla et al. 1996, Mohagheghi et al. 2004, Graci et al. 2010). In contrast, feedback visual information is information relating to the current step being executed (i.e., the current swing phase) and informs an online, conscious, closed-loop motor control system (Marigold 2008). Feedback visual information is necessary to fine tune the pre-made motor plan (Graci et al. 2010) and correct any perceptual errors which may have informed the feedforward plan (McCarville and Westwood 2006, Glover and Dixon 2004). Both feedback and feedforward visual information are necessary to ensure a safe and efficient gait. For instance, when given the choice, people will prioritize collecting feedforward visual information during walking (Patla et al. 1996), but if feedback visual information is removed, people will adopt a more cautious gait pattern to counter any unexpected perturbations (Timmis, Bennett, and Buckley 2009, Timmis and Buckley 2012, Marigold and Patla 2008). The present dissertation therefore examines gaze behavior, specifically fixation distance and visual reliance, to understand how people use feedback and feedforward visual information to guide their locomotion.

Fixation Distance

When walking on flat, level ground, healthy young adults tend to visually fixate about two steps ahead (Patla and Vickers 1997, 2003, Matthis et al. 2018). This average represents the balance of feedback and feedforward visual information collection and persists regardless of the stepping task, including precision stepping (Patla and Vickers 2003), target avoidance (Matthis and Fajen 2013, 2014), and obstacle navigation (Patla and Vickers 1997). Later sections of this chapter will discuss how environmental and individual factors shift this average fixation distance as people prioritize collecting feedback or feedforward visual information. For our purposes, we will use the average of about two steps ahead when walking on flat, level ground as our baseline for comparison with other situations discussed later in the chapter.

Visual Reliance

Visual reliance is defined here as how motor performance changes with the removal of all or certain pieces of visual information. Similar to doing a genetic knockout paradigm in mice, we can explore how pieces of visual information are used during the task by examining how performance changes when such information is removed. There are a few different methods researchers employ to limit the amount or type of visual information available. The first is visual occlusion, whereby people block all or part of a person's visual field, such as wearing a blindfold or with electronic occlusion glasses (Timmis and Buckley 2012, Timmis, Bennett, and Buckley 2009, Buckley et al. 2005, 2008, Craik, Cozzens, Freedman 1982, Marigold and Patla 2008, Rietdyk and Rhea 2006, 2011). Similar to visual occlusion, information removal (Matthis and Fajen 2014, Hollands and Marple-Horvat 1996) is where the relevant information is removed from the environment (such as turning off projected targets, a method I employ in Chapters 5, and 6). A third method is experimentally directed visual fixation, where participants are required to maintain a single fixation point, often directed away from the movement to limit central visual input (Vieluf et al. 2015). For all three of these methods, researchers will compare performance during the limited visual conditions to a full/free viewing condition to determine visual reliance. In some instances, researchers will then add a visual perturbation on top of the limited vision condition, with the relative impact of the visual perturbation being taken as evidence of visual reliance (Yeh et al. 2014, Anson et al. 2014). Unlike fixation distance, there is no universal metric that can be applied to visual reliance. All determinations are relative to the task being performed and, thus, I can only comment on relative changes in visual reliance (such as a general increase in reliance). I will again make these comparisons vs healthy young adults.

When walking in a straight line over flat ground, healthy young adults exhibit almost no visual reliance (Pham et al. 2011). However, adding something as simple as a turn increases their reliance on vision (Pham et al. 2011, Pradeep Ambati et al. 2013). When stepping over an obstacle, feedback visual reliance is evident both during the approach (Patla and Grieg 2006) and execution of the step over the obstacle (Patla et al. 1996, Mohagheghi et al. 2004, Hayhoe et al. 2009, Timmis and Buckley 2012, Lo et al. 2015). Most commonly, this means that people have an increased toe clearance when stepping over the obstacle without feedback visual information (Patla et al. 1996, Mohagheghi et al. 2004, Timmis and Buckley 2012). Feedforward visual information is also relied upon during obstacle crossing (Mohagheghi et al. 2004), and during target avoidance (Matthis and Fajen 2014), with the removal again leading to an increased toe clearance or more variable step placement. Similar feedforward results have been demonstrated in non-walking tasks such as typing based sequence learning (Ariani et al. 2021) and path following (Bashford et al. 2022) with motor performance decreasing with the removal of feedforward visual information.

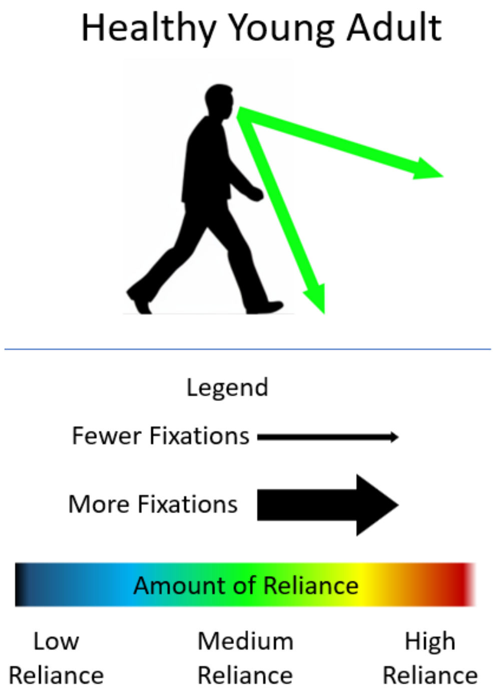

Figure 2-1. Default depiction of where a healthy young adult looks and their visual reliance on feedback and feedforward information. Fixation distance (width of arrows) is evenly weighted between both feedback and feedforward directions, color places them in the middle of our reliance scale.

We can therefore start by defining the gaze behavior of a healthy young adult (Figure 2.1). They perform a mix of feedback and feedforward fixations creating an average fixation distance of about two steps ahead. They also have a moderate reliance on both feedback and feedforward visual information allowing for room to both increase and decrease their reliance based on the situation (as we will see in the following sections).

The Effect of Terrain

Fixation Distance

The terrain a person is navigating can have several effects on their gaze behavior. When walking on easy, flat terrain with no obstacles, such as a paved path, a person’s gaze is often not directed towards the locomotor path (Matthis et al. 2018) and instead is guided by the visual salience of the environment (Turano et al. 2003). However, when the terrain gets more complex, the gaze will be directed downwards, fixating more on the path and eventually straight down at their own feet (Thomas et al. 2020a, b, Marigold and Patla 2007). The effect of the terrain is graded, such that the more complex the terrain is to navigate, the closer to themselves a person will fixate

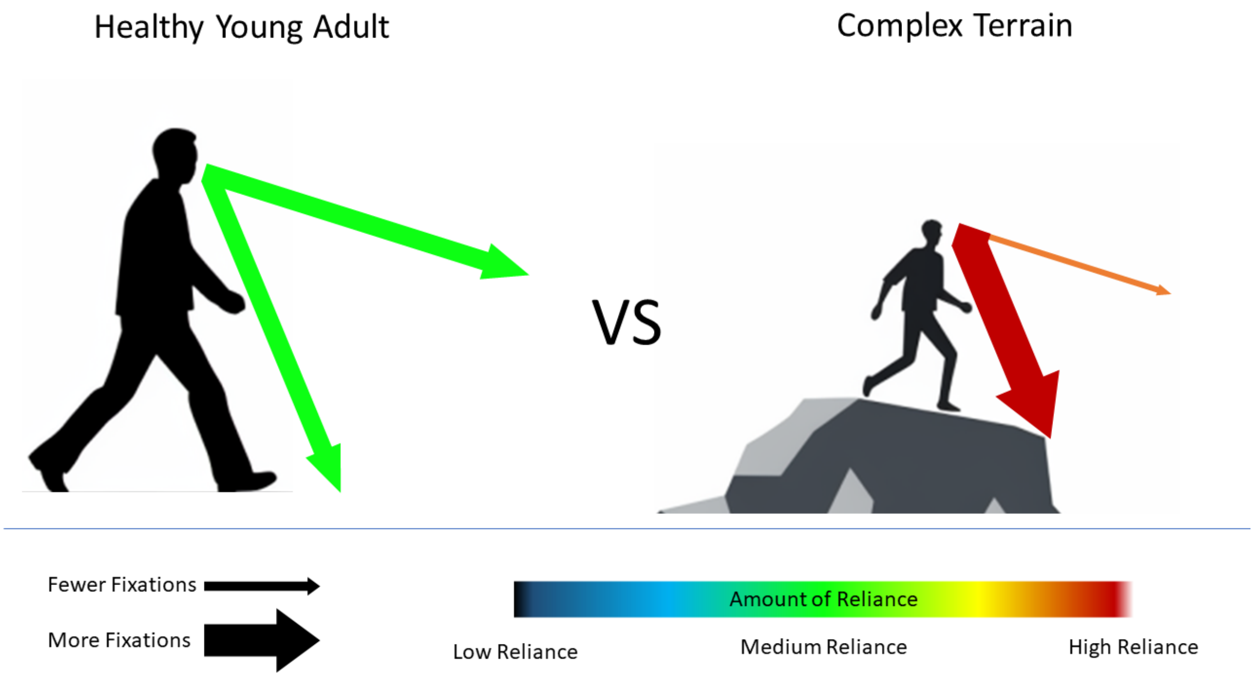

Figure 2-2: Comparison between healthy young adults on flat terrain (Left) vs healthy young adults on complex terrain (Right) of where they direct their vision (arrow thickness) and the amount they rely on vision (color).

(Matthis et al. 2018). Therefore, walking on complex terrain increases the number of feedback fixations and decreases the number of feedforward fixations, reducing the overall average fixation distance (Figure 2.2).

Visual Reliance

The shift in fixation distance likely also suggests a shift in visual reliance. Visual occlusion studies have demonstrated an increased reliance on feedback visual information when navigating complex terrains (Marigold and Patla 2008). Additionally, when clearing an obstacle (a simple complex terrain) feedback visual reliance also increases (Patla and Vickers 1997, Patla et al. 1996, Patla and Grieg 2006, Graci, Elliott and Buckley 2010). During stair descent, occluding feedback visual information leads to a more cautious, “soft” landing behavior (Timmis, Bennett, and Buckley 2009, Buckley et al. 2007, Craik, Cozzens, and Freedman 1982). While the research on how terrain affects feedforward visual reliance is limited to lab studies (Matthis and Fajen 2014, Graci, Elliott, and Buckley 2010), they do suggest that there is a general increase in visual reliance. Overall, there is clear evidence that complex terrains increase feedback visual reliance. Similarly, complex terrains seem to increase feedforward visual reliance, however more research is likely needed to support this conclusion.

Overall, complex terrain decreases a person’s fixation distance and increases feedback visual reliance and likely feedforward visual reliance (Figure 2.2). Based on the available literature, the locomotor research presented in this dissertation will create a simulated complex environment through the use of projected stepping targets. This will allow for enough dynamic range for changes in fixation distance and visual reliance to be identified in both healthy individuals and individuals post-concussion.

The Effect of Age

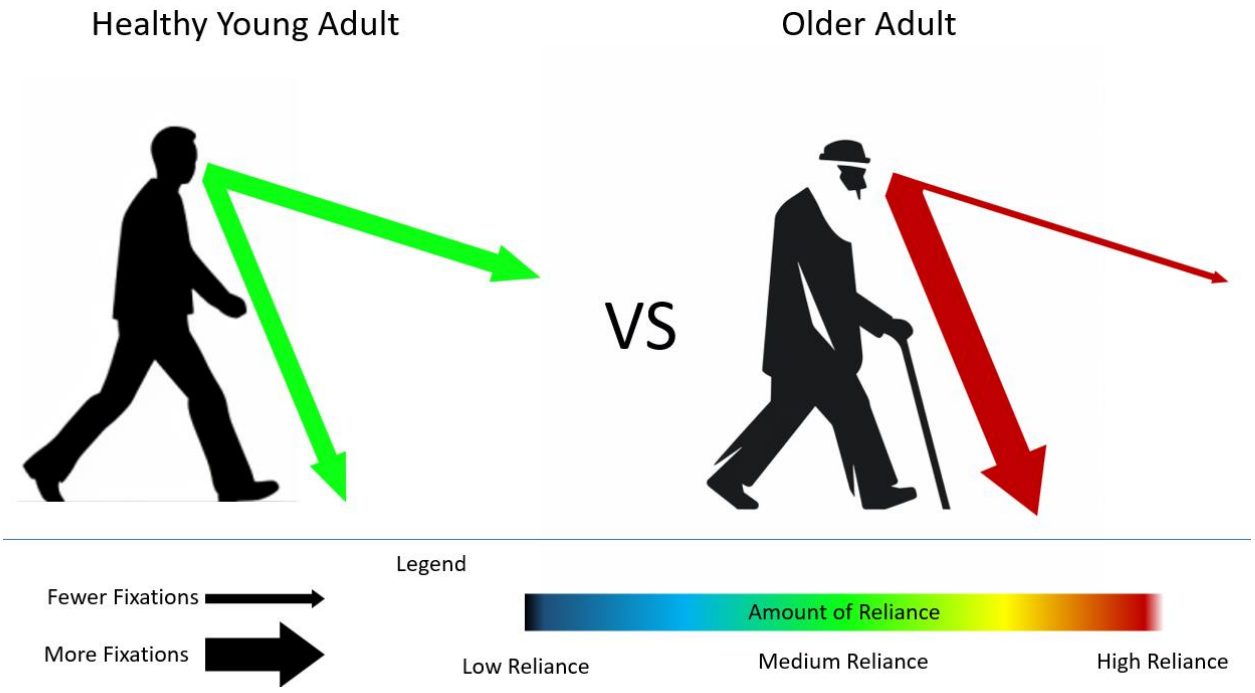

Figure 2-3: Comparison between healthy young adults on flat terrain (Left) and older adults on complex terrain (Right) of where they direct their vision (arrow thickness) and the amount they rely on vision (color).

Fixation Distance

Older adults tend to fixate closer to themselves than young adults (Figure 2.3). Whether it is a target stepping task (Chapman and Hollands 2006), stair climbing (Zietz and Hollands 2009), obstacle avoidance (Muir et al. 2015), or complex terrains (Hunt et al. 2023, Dominguez-Zamora et al. 2020), older adults perform more feedback fixations and look closer to themselves on average. The reduced fixation distance is also accompanied with a disruption in fixation timing, with older adults spending more time fixating on their path (Zukowski et al. 2020). We can therefore see that age, similar to terrain, reduces fixation distance. While the effect is consistent, it may not be a bad thing as further decreasing the fixation distance of older adults, by directing their gaze through verbal reminders, improves stepping performance (Young and Hollands 2010).

Visual Reliance

Older adults also exhibit greater visual reliance, both in terms of general reliance and specifically for feedback visual reliance (Figure 2.3). When vision is completely occluded, such that they receive no visual information, older adults change their gait patterns more than young adults, becoming overly cautious when navigating an obstacle (Kunimune and Okada 2017). Their visual reliance is increased even after the movement has started (Chapman and Hollands 2006), demonstrating the need for older adults to visually guide and adjust ongoing movements. When feedback visual reliance is directly probed through partial visual occlusion, older adults again adopt a more cautious gait pattern (Marigold and Patla 2008). Additionally, older adults are more perceptible to visual perturbations, such as artificial optic flow fields which perturb their perception of locomotor steering (Yeh et al. 2014), suggesting an increased reliance on feedforward visual information. As mentioned, some recent trial interventions have improved stepping performance directing older adults to focus on feedback visual information, effectively reducing feedforward reliance and increasing feedback reliance in the process (Young and Hollands 2010).

Overall, similar to complex terrains, older adults fixate closer to themselves and rely on visual information, both feedback and feedforward visual information, more (Figure 2.3). While not the focus of the present dissertation, the changes in gaze behavior due to aging informed my expectations of how other gait-deficient populations (i.e., individuals post-concussion) may perform.

The Effect of Neurologic Impairment

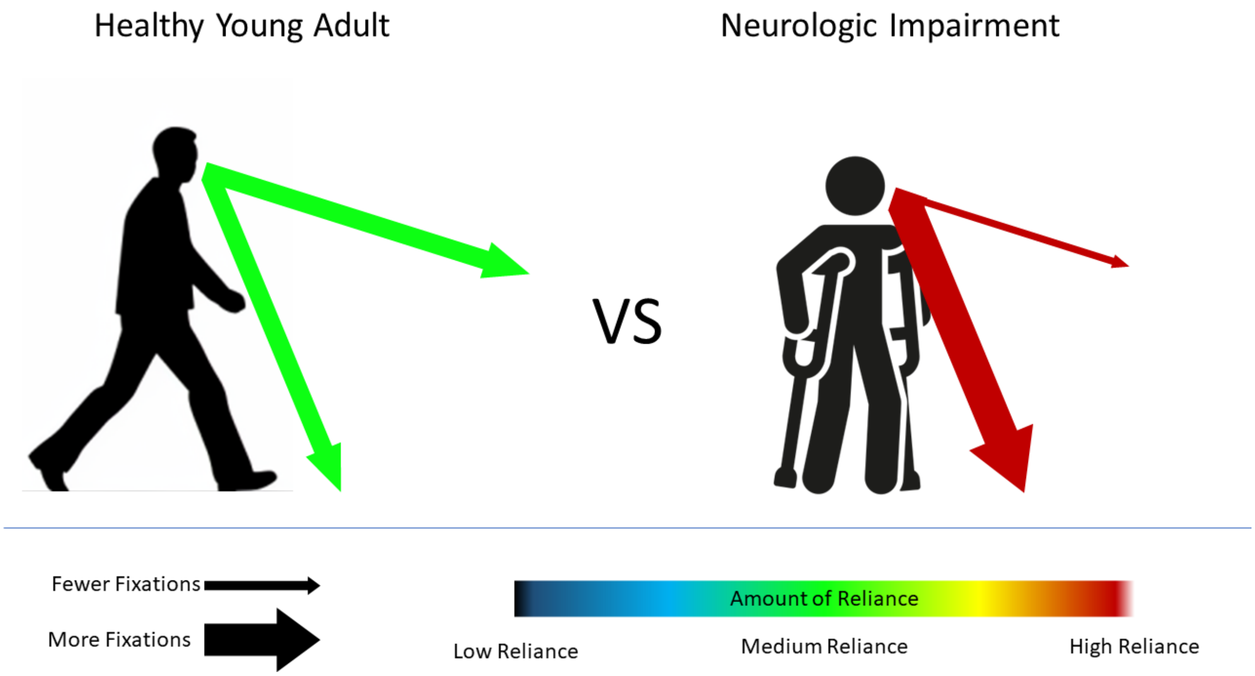

Figure 2-4: Comparison between healthy young adults on flat terrain (Left) vs individuals with neurologic impairments (Right) of where they direct their vision (arrow thickness) and the amount they rely on vision (color).

Fixation Distance

The gaze behaviors of several populations with neurological impairments have been examined to better understand the causes of their gait deficits. Following an incomplete spinal cord injury, people will fixate closer to themselves during an obstacle crossing task (Malik et al. 2017). A similar reduction in fixation distance is found among people with developmental coordination disorders during a walking task (Warlop et al. 2020). People with Parkinson’s Disease exhibit task-based changes to their fixation patterns. When walking over flat ground, people with Parkinson’s Disease look farther ahead and at more task-irrelevant information (Hunt et al. 2018). However, when they have to cross an obstacle, they fixate closer to themselves and hyper-fixate on the obstacle itself (Hunt et al. 2018). However, when people with Parkinson’s have to navigate multiple targets, they may prematurely transfer their gaze to a future target, increasing their step error and their fixation distance (Vitorio et al. 2016). Overall, similar to older adults, we generally find neurological impairments reduce a person's fixation distance (Figure 2-4).

Visual Reliance

When visual reliance is examined in populations with neurologic impairments, we see a similar increase in visual reliance as was observed in older adults. People with Parkinson's Disease exhibit a general increase in visual reliance during obstacle crossing (Simieli et al. 2017, Vitorio et al. 2013). Individuals with chronic stroke exhibit a disruption in optic flow perception (Lamontagne et al. 2010) and the integration of visual information with the coordination of body movements during turning (Lamontagne et al. 2007, Lamontagne and Fung 2009). Similarly, people with multiple sclerosis are more susceptible to visual perturbations (Selgrade et al. 2020), again suggesting a general increase in visual reliance.

Overall, neurologic impairments decrease fixation distance and increase visual reliance (Figure 2.4). However, more research is needed to differentiate between feedback or feedforward visual reliance in these populations.

The Effect of a Concussion

One notable absence from the literature on gaze behavior neurological impairments is individuals post-concussion. Concussions are one of the most common neurological injuries in America, with an estimated 4 million people diagnosed with a concussion every year (Harmon et al. 2013). In the acute stages (generally the 2 weeks following the injury), concussions lead to a wide range of symptoms including cognitive (Parker et al. 2007), oculomotor (Murray et al. 2019), vestibular (Ellis et al. 2015) and gait (Wood et al. 2019) deficits. While most of these symptoms resolve after the acute stage, recent research has found that gait deficits often persist for weeks or months following the injury (Wood et al. 2019); leading to comorbidities such as a 3x increase in the risk of a lower leg injury (Herman et al. 2017). This persistence of gait deficits and the increased injury risks suggest a change in locomotor control, though the mechanisms behind this change are currently unknown.

Gaze behavior offers one potential mechanism behind the hypothesized changes to locomotor control. Eagle and colleagues (2020) proposed exactly this, suggesting that people post-concussion may be misperceiving the world around them, leading to altered gait patterns. Given the oculomotor deficits present during the acute stages (Murray et al. 2019), which limit what information a person is able to collect, people post-concussion may exhibit changes in their gaze behavior. If people post-concussion behave similarly to other populations with neurological impairment, we would expect people post-concussion to fixate closer to themselves and to rely on feedback visual information more. Chapter 6 will therefore examine where people post-concussion direct their gaze and how they rely on visual information while practicing a precision stepping task.

The Effect of Confidence and Anxiety

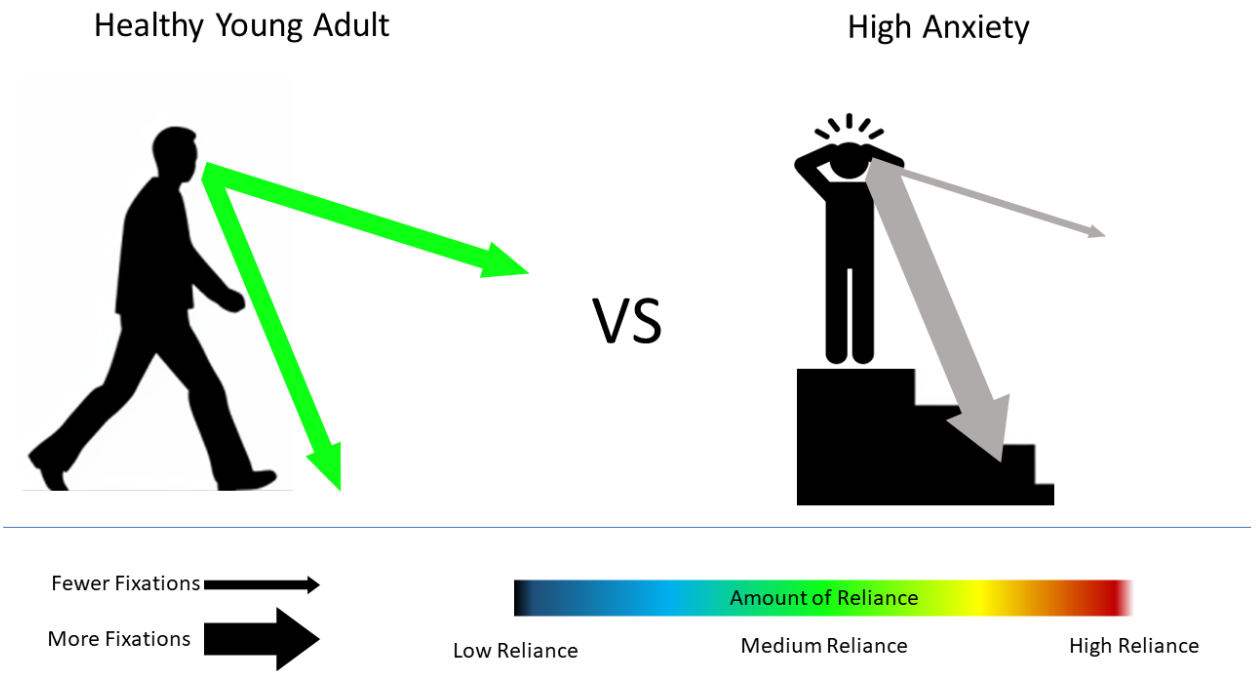

Figure 2-5: Comparison between healthy young adults on flat terrain (Left) vs an individual with high anxiety (Right) of where they direct their vision (arrow thickness) and the amount they rely on vision (color). In this instance, gray arrows represent unknown changes in visual reliance.

Fixation Distance

Decreasing a person’s confidence and increasing their fall related anxiety may also reduce their fixation distance. When fall related anxiety is increased through changing the height of a walking platform, people reduce their fixation distance (Ellmers et al. 2019, Kluft et al. 2020). Similarly, when people view a terrain as more difficult, they fixate closer to themselves to better inform the cautious approach they take (Thomas et al. 2020c). One possible mechanism for this effect is a shift towards more conscious processing of the movements (Ellmers et al. 2020a, b) and a more externally directed focus (Mak et al. 2020). Regardless of the mechanism, the effect is that people will look closer to themselves when they are not confident in their walking ability.

Visual Reliance

To my knowledge, the effect of confidence or anxiety on visual reliance has not been examined. This may be a point of future study but was not explored in the present dissertation.

Overall, we can see that reducing a person's confidence leads to a reduction in average fixation distance (Figure 2.5). The effect of confidence was considered in both the design and interpretation of the studies presented here. In particular, Chapter 5 discusses confidence as a possible explanation for the differences seen in fixation distance compared to Chapter 4.

The Effect of Elite Athleticism

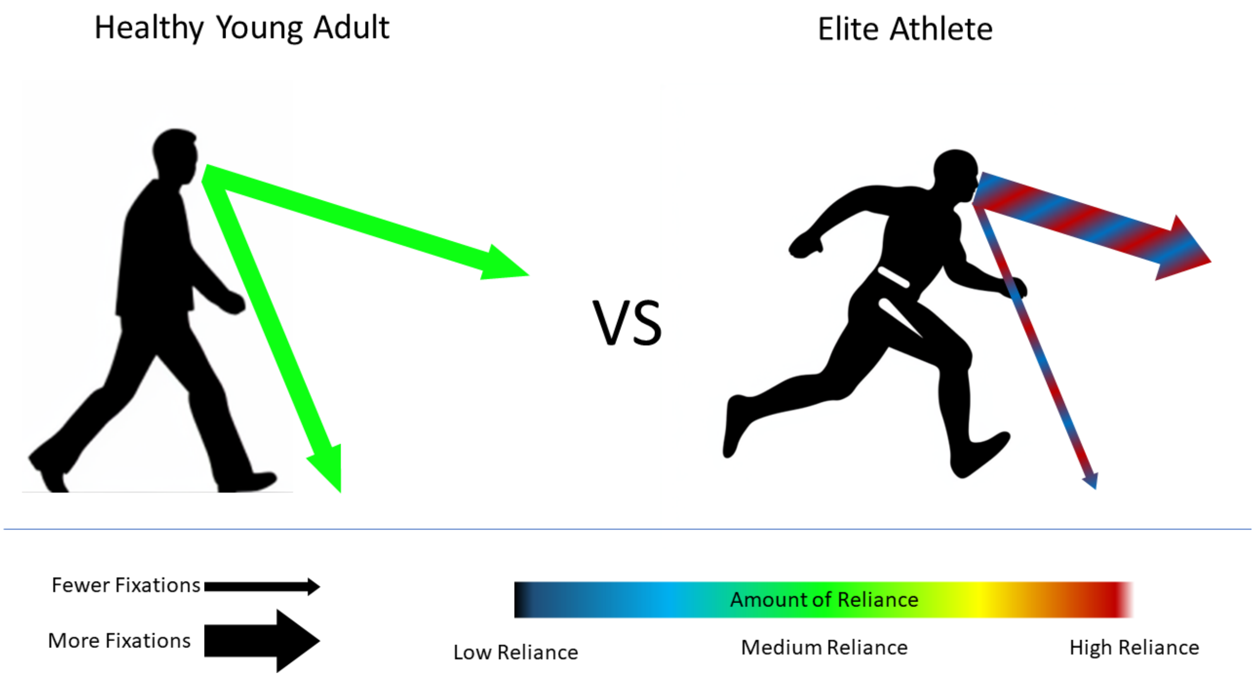

Figure 2-6: Comparison between healthy young adults on flat terrain (Left) vs Elite Athletes (Right) of where they direct their vision (arrow thickness) and the amount they rely on vision (color). Because evidence suggests both increasing and decreasing visual reliance among elite athletes, the arrows are striped with both red and blue.

Fixation Distance

Elite athletes also show altered gaze behavior compared to novices or non-athletes. Soccer players will fixate farther ahead when they don't have the ball (Aksum et al. 2020), though where they look while taking a penalty kick does not seem to affect performance (Kurz et al. 2018). Elite volleyball players similarly fixate farther ahead than novices when watching a replay of their game (Piras et al. 2010). In video games, elite guitar hero players fixate farther ahead (in terms of the game screen) than novices (Vickers et al. 2010). Together, the research suggests elite athletes fixate farther ahead (Figure 2.6).

Visual Reliance

When we examine the visual reliance of elite athletes, we find a variety of research finding altered visual reliance, though the direction of the changes may be sport or task specific. Elite gymnasts performing a vault fixate on their landing spot less than novices, relying more on proprioception and suggesting a general reduction in visual reliance (Natrup et al. 2020). Soccer goalkeepers and cricket batsmen exhibit a general reduction in visual reliance (Makris and Urgesi 2015, Brenton et al. 2016). In contrast, elite basketball players exhibit a greater reliance on feedback fixations during shooting (Oudejans et al 2002, 2012). Elite golfers often exhibit quiet eye performance, a form of gaze behavior focused on extending the duration of the last fixation before striking the ball (Harris et al. 2020, Carnegie et al. 2020). Depending on they direct this final fixation, golfers may be increasing their reliance on feedback or feedforward visual information, but either scenario improves performance (Xu et al. 2021). In general, while it is likely that elite athletes have altered visual reliance, the specifics of feedback vs feedforward reliance, or whether visual reliance is increasing or decreasing, may be sport specific (Figure 2.6).

The gaze behaviors of elite athletes were considered as the eventual endpoints of any motor learning paradigm (described further below). Importantly, how motor learning leads to changes in gaze behavior, specifically during walking, is poorly understood. This dissertation begins to address this gap and my hypotheses were informed by the hypothetical endpoint of the differences between novice and elite athletes.

The Effect of Motor Learning

While the studies presented here focus on healthy, young, non-elite-athlete adults, the consistent effects of both aging and neurologic impairments (reducing fixation distance and increasing visual reliance) compared to elite athletes (increasing fixation distance) suggests that there may be a connection between motor skill/ability and gaze behavior. However, an important question is how do these differences develop? And, how can we shift our gaze behavior to improve both rehabilitation and elite athletic training?

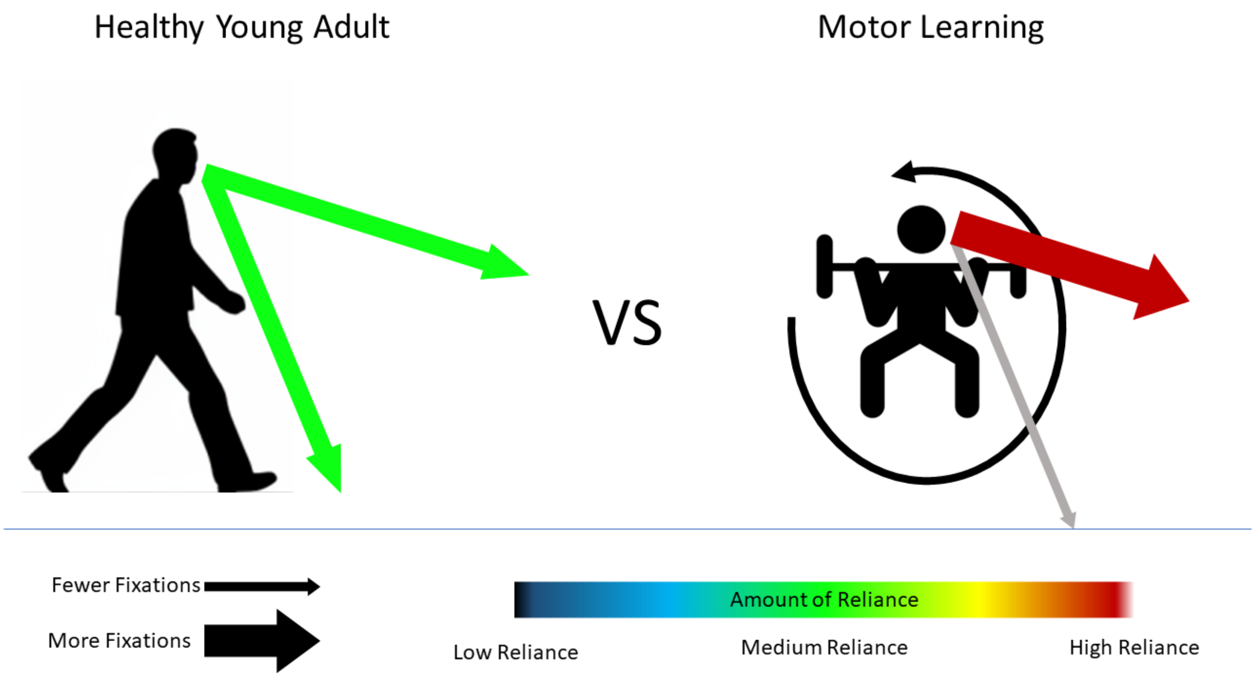

Figure 2-7: Comparison between healthy young adults before practicing a motor task (Left) vs after practicing the motor task (Right) of where they direct their vision (arrow thickness) and the amount they rely on vision (color). The gray arrow represents an unknown area of the literature.

Fixation Distance

A few studies have begun to examine how fixation distance or location changes with motor learning. Sailer and colleagues (2005) demonstrated that where people look changes with motor learning, with practice of a novel curser movement task leading to a decrease in fixations on the curser and an increase in fixations on the ballistic target. Follow-up studies have largely supported this result across ballistic curser movements (Safstrom et al. 2014), reaching (Vieluf et al. 2015, Perry et al. 2020), and driving (Tuhkanen et al. 2021), though there is competing evidence in a trail following task suggesting no change in fixation distance (Mathew et al. 2019). When we focus on walking, we find additional, though limited, support for fixating farther ahead. Kopiske and colleagues (2021) examined how people identify and prepare for an icy patch when navigating a virtual walkway. Participants looked farther ahead with practice to prepare for the slip. A follow-up study replicated the results (Muller et al. 2023), suggesting that people also look farther ahead with locomotor practice. However, whether these results generalize to a continuous target stepping task is unknown. Overall, we would expect fixation distance to increase with motor learning, but how well that translates to locomotor learning remains to be established and is the focus of Chapter 4.

Visual Reliance

Indirect evidence from reaching and finger coordination studies suggests that feedforward visual reliance increases with practice (Mennie et al. 2007, Perry et al. 2020, Ariani et al. 2021, Bashford et al. 2022); though some of these studies (Ariani et al. 2021, Bashford et al. 2022) may be evidence of an increase in visual flexibility, or the ability to perform under any visual condition, more so than an increase in visual reliance. In walking studies, there is indirect evidence of a general decrease in visual reliance which can be impacted by dual task interference during locomotor learning (Muller et al. 2023). However, further research is needed to determine how visual reliance changes with locomotor learning and is therefore the focus of Chapter 5.

Current State of What Alters Gaze Behavior

In general, after reviewing several different situations that alter gaze behavior, a general pattern emerges. Situations that make walking harder (Aging, Neurological Impairment, Anxiety, Complex Terrain) lead to a reduction in fixation distance and an increase in visual reliance (notably feedback reliance). In contrast, situations that make walking easier (elite athleticism, motor learning) increase fixation distance, though the effects on visual reliance remain mixed.

Scientific Gap

The literature review emphasizes a couple of gaps which will be the focus of the present dissertation. First, does gaze behavior change as a consequence of motor skill changes or is it a cause of motor skill changes? While previous research has established that gaze behavior may change with motor learning, whether it is a cause of those changes that can then be used for interventions is unknown. Chapter 3 will focus on this question using an online motor learning paradigm. Second, does gaze behavior change with locomotor learning? Most of the research has focused on upper limb motor learning paradigms and while there is lots of evidence for differences in gaze behavior during walking, these are at the end points, comparing a novice vs an expert or a healthy young adult with a gait deficient individual. Therefore, we do not know how the differences in gaze behavior came to be. Chapters 4 and 5 will focus on this question, examining how locomotor learning changes fixation distance (Chapter 4) and visual reliance (Chapter 5). Finally, how does a concussion affect gaze behavior during walking? Visuomotor deficits may contribute to the persistent gait deficits reported and provide possible intervention points. Chapter 6 will therefore focus on whether gaze behavior during walking is altered after medical clearance from a concussion.

Chapter 3: Motor learning alters vision, but vision does not alter motor learning

Chapter 3 presents research on how visual reliance changes during an online motor learning task. While the experiments presented do not involve a walking task, it provides important context for how visual reliance changes in a more traditional motor learning task. Additionally, Chapter 3 covers the reverse, investigating whether visual availability alters motor learning. The results provide important context for implementing future gaze training protocols.

Abstract

During visuomotor learning, improvements in motor performance accompany changes in how people use vision. However, whether altered visual reliance causes improvements in motor skill or vice versa is unclear. The present studies used an online sequence learning task to quantify how changing the availability of visual information affected motor skill (Experiment One) and how changing motor skill affected visual reliance (Experiment Two). Participants played an online game where they pressed corresponding keys when a target reached the bottom of the game screen. In Study One, the availability of visual information was altered by manipulating where the targets were visible on the screen. Three experimental groups practiced the task during full or limited vision conditions (when the targets were only visible in specific areas). We hypothesized that limiting visual information would reduce motor learning (i.e., the rate of improvement during training). Instead, while participants performed worse during limited vision trials ($p<0.001$), there was no difference in learning rate ($p=0.87$). In Experiment Two, all participants practiced the task with full vision and their visual reliance (i.e., their performance

change between full and limited vision conditions) was quantified before and after training. We hypothesized that with motor learning, visual reliance would increase for some visual areas and decrease for others. The results of Experiment Two partially support our hypotheses with motor learning decreasing visual reliance for all visual areas ($p<0.001$). Together, the results suggest changing motor skill alters how people use vision, but changing visual availability does not affect motor learning.

New & Noteworthy

Previous research has established how people use visual information changes with motor learning. However, the dependencies between these two processes are unclear. We find that limiting the availability of visual information degrades motor performance but not motor learning. We also find that motor learning reduces the impact of limiting the availability of visual information on motor performance. Together, these results suggest that changes in visual processing are dependent on changing motor skill.

Introduction

Motor learning is the process of improving a movement with practice. The learning process involves constantly updating, altering, and optimizing the movement. As the accuracy of the movement improves with practice, the motor control strategies will also change. Novices typically use a feedback, or closed loop, control strategy where they actively correct a movement while it is being executed. As their skill develops, they progress to a feedforward, or open loop, motor control strategy, letting the planned movement complete its execution before updating the motor plan for the next action (Franklin and Wolpert 2011, Khan and Franks 2004). Similarly, the sensory information used to execute the movement will change with the motor control

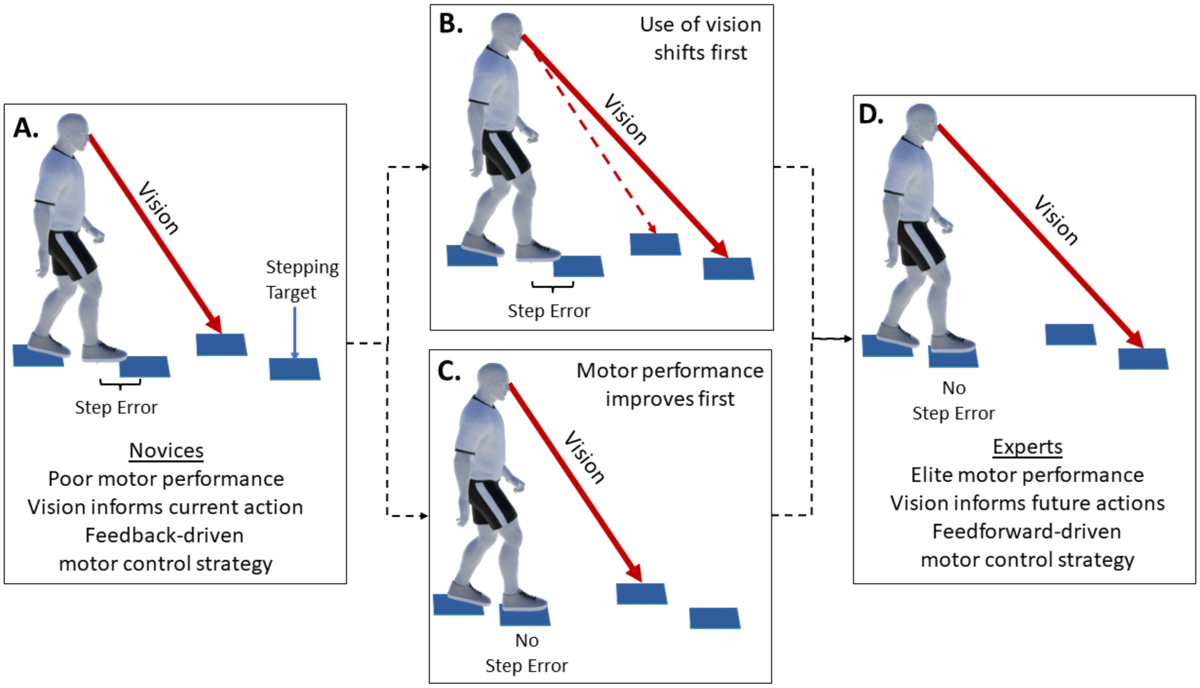

Figure 3-1: Theoretical framework of how motor control strategies change during motor learning. Previous research has established that Novices (A) and Experts (D) use different visual and motor control strategies to perform the same task (such as walking in the image). However, what the intermittent states of these changes and/or whether visual strategy (B) or motor performance (C) change first is unknown

strategy. For visuomotor control, novices tend to fixate on information about future actions (Bashford et al. 2022). However, whether changing what visual information is gathered changes the motor control strategy or vice versa is unclear (Figure 3-1).

The correlational relationship between visual information and motor control strategies is well documented in a variety of motor learning tasks. Whether people are controlling a cursor on a computer (Sailer et al. 2005), playing video games (Vickers et al. 2010), reaching for a target (Perry et al. 2020), or stepping on (Cates and Gordon 2022) or avoiding (Kopiske et al. 2021) targets on the ground, a progression from fixating on the object being manipulated to fixating on the target is characteristic of motor learning. This gaze shift also occurs whether the task consists of intermittent targets (Sailer et al. 2005, Kopiske et al. 2021) or a continuous stream of targets for the individual to navigate (Vickers et al. 2010, Perry et al. 2020, Cates and Gordon 2022) suggesting neither the type of motor task nor muscle groups used affect the relationship. For the motor control strategy to change, previous literature generally assumes that first a person’s motor performance changes, then their visual behavior changes to support the new motor control strategy (As proposed by Sailer et al. 2005 and Perry et al. 2020 and represented in the progression in Figure 3-1 of A → C → D). However, recent research which manipulates what visual information is available suggests otherwise.

Research on visual occlusion during motor learning suggests that visual sampling strategies may need to change before motor performance can improve. When visual information is removed or constrained, motor learning becomes impaired (Massing et al. 2016, Vieluf et al. 2015). While this directly suggests that changing visual information changes motor learning, there are additional variables that need to be considered. When visual information is constrained, people perform worse on a task (e.g., Timmis and Buckley 2012). It may be that degraded motor performance (rather than the altered visual information) impairs motor learning. For example, limiting visual information about the current action causes people to step less accurately (Kim et al. 2018, Timmis and Buckley 2012). Similarly, limiting visual information used to plan future movements (such as information about a target three steps ahead) reduces movement accuracy during walking (Matthis et al. 2015), playing computer games (Ariani et al. 2021), and executing full-body movements (Saeedpour-Parizi et al. 2020). Ballester and colleagues (2015) demonstrated that when people perform poorly on a task, it is hard for them to improve because they struggle to find the correct motor pattern to optimize and thus, they do not progress their motor control strategy. Taken together, limiting visual information may just worsen immediate performance, rather than directly impacting motor learning.

Despite the mixed understanding of cause and effect, there is an interaction between motor learning and vision. Consequently, vision training is being tested as a possible intervention to improve motor performance (Young and Hollands 2010, Gunn et al. 2019). Participants are taught where to look with the expectation that improvement in motor skill will follow. While these studies have shown some preliminary positive effects, there is not a clear separation between the visual and motor training. Instead, these efforts often include reminders to focus on vision while participants practice the task. To properly develop these interventions, we need to understand the exact role of vision during motor learning, and the cause-and-effect relationship between vision and motor skill. Therefore, to better understand the interplay of changes in gaze behavior and improvements in motor skill, we performed two experiments that each used an online motor learning paradigm to investigate how manipulating vision or motor performance changes motor learning or visual behavior, respectively.

In Experiment One, we measured how altering what visual information is available to the participant during the motor learning process impacts both the learning rate and performance. We altered visual availability by limiting where targets were visible on a game screen, specifically hiding the targets when fixating upon them would inform feedback or feedforward motor control strategies. We hypothesized that motor learning would be impaired by the limited visual conditions. Specifically, we expected that removing information about future actions would not affect initial learning, but overtime would limit overall motor learning and create significant group differences in later trial blocks. This is because removing information about future actions should not impair feedback control processes, which is the primary control process used by novices (Franklin and Wolpert 2011). Only once a novice has improved enough to emphasize feedforward motor control strategies would the lack of information about future actions impair their motor learning. In contrast, we expected removing information about the current action would prevent motor learning by removing visual knowledge of the result (Oppici et al. 2021). Such findings would indicate that motor learning depends on specific visual information at specific stages of the motor learning process, with feedback visual information needed for early learning (not just preferred) and that without it, participants are unable to progress the skilled feedforward stage.

In Experiment Two, we measured how motor learning altered gaze behavior by quantifying participant reliance on feedforward and feedback visual information to perform the task. We defined visual reliance as the amount a participant's performance decreased when the relevant visual information was removed. We hypothesized that, similar to general motor control theory where people shift from focusing on a feedback to a feedforward information (Franklin and Wolpert 2011, Kahn and Franks 2004), participants' reliance on feedback visual information would decrease and their reliance on feedforward visual information would increase with motor learning (matching a progression from feedback to feedforward motor control strategies). Such results would support that the role of vision is guided by motor skill.

Taken together, the outcomes of these studies provide information about the dependent relationship between gaze behavior and motor learning. Experiment One assesses how gaze affects motor learning, while Experiment Two assesses how motor learning affects gaze. The two studies provide complementary evidence of the cause-and-effect relationship between gaze and visuomotor learning.

Methods

Participants

197 participants (52 for Experiment One and 145 for Experiment Two) were recruited through social media and Amazon Mechanical Turk. In Experiment One, participants' mean age was 33.4 years old (18-65) with 23 women. In Experiment Two, participants mean age was 35.8 years old (19-65) with 43 women. For each experiment, participants recruited through social media were entered into a raffle to win $100, while participants recruited through Amazon Mechanical Turk received $3 for completing the study. All participants completed an online informed consent and participated on their personal computers from a remote location of their choice. All procedures were approved by the Northwestern University Institutional Review Board (IRB).

Online Learning Task

In both studies, participants completed repeated trials of an online finger coordination task. Targets would stream, vertically, from the top to the bottom on the game screen at a constant speed. Targets would be dropped from one of four locations, with each location mapped to a key on the keyboard ("J", "K", "L", ";" keys for right-handed individuals, "A", "S", 'D", "F" for left-handed individuals). Participants used a separate finger for each key (index to pinkie).

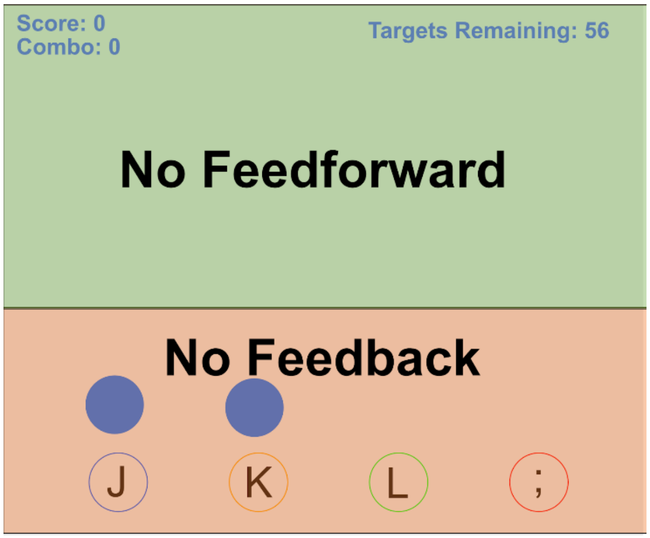

Figure 3-2: Still image of the online learning task with the areas where the targets could be hidden highlighted. Participants had to respond whenever a target (blue circle) aligned with one of the open response circles (surrounding the key labels) with the corresponding key. Targets were hidden in the orange zone during the No Feedback condition and hidden in the green zone during the No Feedforward condition.

In Experiment One, participants were required to have the appropriate key(s) pressed when the target(s) aligned with the circle at the bottom of its path (See Figure 3-2). A successful response was defined as having only the correct key(s) pressed when the target(s) aligned with its respective response circle.

In Experiment Two, following feedback from participants, the response instructions were changed such that participants only had to perform a single press of the key when the target was near its response circle to signify a response rather than holding the key while the target aligned. A key press within 1.5 target diameters of the center of the response circle was accepted as accurate. This change was made to make the task more natural and to better conform to participant expectations.

In both studies, participants received feedback on their performance in the form of an auditory “ding” in response to a successful response. A combo (number of correct responses in a row) and score counter displayed in the top left of the game screen. The combo and score were for motivational purposes only and increased with each correct response.

The targets progressed down the game screen at a constant rate, taking a total of 1.4 seconds to traverse the entire game screen. Zero to two targets would start down the screen every 0.6 seconds. In cases where zero targets were released, it created a longer pause between targets to avoid too much rhythmicity within the task. The order of targets was either random or sequenced (See Trial Blocks and Conditions for definitions). The embedded sequence was used to accelerate the motor learning and to test whether any changes were sequence specific (Experiment Two).

To test the importance of vision on feedback and feedforward motor control, we defined areas on the game screen to correspond to the visual information related to these motor control strategies (highlighted in Figure 3.2). Feedback information was defined as information relating to the current action (in this case the current target(s) the participant must respond to). Given the target speed, the bottom 40% of the game screen provided information about the current target(s). Feedforward information was defined as information about future targets, in this case corresponding to the upper 60% of the game screen.

Trial Blocks and Conditions

The following terms are used throughout the methods to describe different settings experienced while playing the online learning task. The different visual conditions were used in both Experiment One and Experiment Two. The sequenced and random trial blocks were used in Experiment One, while all our trial block types were used in Experiment Two (Figure 3-3).

Full Vision Condition: The control condition where targets were visible for their entire path down the game screen.

No Feedback Condition: During the no feedback condition, the targets were visible for the upper 60% of the game screen (a total of 0.8 seconds) and hidden in the bottom 40% (the orange area in Figure 3-2). The no feedback condition was used to assess the role of feedback visual information on motor learning and motor performance. Participants were still expected to respond to each target when it reached its respective response circle, even though the target(s) were not visible. Participants therefore had to predict when the target reached the response circle and respond appropriately. They would still receive auditory feedback based on the accuracy of their response.

No Feedforward Condition: During the no feedforward condition, the targets were visible only for the lower 40% of the game screen (a total of 0.6 seconds) and hidden in the upper 60% (the green area in Figure 3-2). The no feedforward condition was used to assess the role of feedforward visual information on motor learning and motor performance.

Trial Block: A Trial Block represented one play-through of the online learning task. Each trial block consisted of a predefined number of targets (with each target representing a single trial) which took differing amounts of time (see different trial blocks below). Participants were able to pause and take a break between trial blocks, but once a block started, they were required to complete it.

Sequenced Trial Block: A trial block where the targets were presented in a repeating sequence. The sequence consisted of a 13-target repeating pattern which was repeated for a total of 195 targets per sequenced trial block. The same 13 target pattern was used in every sequenced trial block and each sequenced trial block took 2 minutes to complete.

Random Trial Block: A trial block where the targets were presented in a random order. These trial blocks were shorter than the sequenced trial blocks, consisting of a total of 85 targets and taking about 1 minute to complete.

Catch Trial Block: A version of the sequenced trial block with a different 13-target repeating pattern. The same 13-target pattern was used in every catch trial block.

Probe Trial Block: Sequenced or Catch Trial Blocks where participants experienced either the no feedback or no feedforward visual conditions (described above). In Experiment Two, these trial blocks were compared to the most recent full vision trial block to probe participant's visual reliance.

Experiment Procedures

In Experiment One, participants completed a total of 8 trial blocks (Figure 3-3A). Participants first completed a practice and baseline trial block, each with full vision and random target sequences. Participants were then randomly assigned to one of three experimental groups during the five training blocks. Each training block consisted of a sequenced trial block with one of the three visual conditions (based on their experimental group). Finally, all participants completed a full vision sequenced trial block post-training to assess motor performance without any visual limitations before and after training.

In Experiment Two, participants completed a total of 14 trial blocks (Figure 3-3B). Participant visual reliance was probed before and after practicing the learned sequence and again with the catch sequence. While the full vision condition was always first during the probe periods

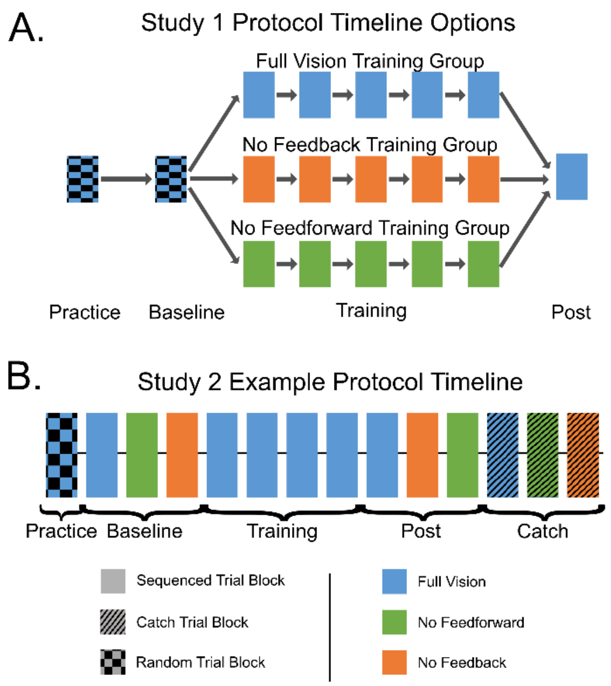

Figure 3-3: A. The three different trial block orders assigned to the different experimental groups in Experiment One. B. A representative trial block order for Experiment Two. The order of the limited vision probe trials changed per participant.

(Baseline, Post, and Catch), the order of the no feedback and no feedforward conditions was randomized for each participant to avoid order effects during the Baseline, Post, and Catch periods. The 4 training trials were presented with the full vision condition to allow participants to train and test without visual limitations.

Outcome Measures

The following outcome measures were used in one or both studies.

Trial Accuracy: Trial accuracy was determined for each trial block as the percentage of targets correctly responded to and used as the metric of motor performance.

Normalized Performance: Normalized performance was calculated as the percent change in trial accuracy from each individual's baseline, full vision trial block.

Improvement Rate: A first order linear regression was used to calculate the improvement rate based on individual changes in normalized performance across consecutive trial blocks with the same conditions. In Experiment One, an improvement rate was calculated for the training trial blocks of each participant. The improvement rate was considered a metric of motor learning, with a more positive slope being indicative of improved motor learning.

Visual Reliance: Visual reliance was calculated as the difference in normalized performance between a probe trial and the most recent full vision condition. For example, the baseline feedback reliance was calculated as the difference in normalized performance between the no feedback condition, probe trial block and the full vision condition, probe trial block during the baseline period. A separate visual reliance metric was calculated for both feedback and feedforward visual reliance.

Data Analysis

To ensure data quality, any participant who was in the bottom 5% of raw (non-normalized) trial accuracy for any individual trial block was removed. For instance, if a participant was in the bottom 5% for only the first training trial block, their entire dataset was removed, even if they performed the rest of the trial blocks to an acceptable level. These normally indicated participants who did not properly complete the task or did not complete the entire task. A total of 3 out of 52 participants from Experiment One and 28 out of the 145 participants from Experiment Two were removed due to this.

Experiment One

To assess the effect of visual condition on motor learning, a linear mixed model was performed using participant data during the training trials. Normalized performance was set as the outcome measure, trial block number, visual condition, and their interaction were set as fixed effects and subject was a random effect. A significant main effect of trial block number would be evidence that participants were able to learn the motor task, while a significant main effect of visual condition would be evidence that removing feedback or feedforward visual information affected performance. Finally, a significant interaction between trial block number and visual condition would be evidence that the visual condition affected motor learning.

To support any interaction effect found in Experiment One, we also conducted a one-way ANOVA to compare the effect of visual condition on improvement rate. If a significant effect was found, a Tukey post hoc test was performed to determine pairwise comparisons. Any significant effects would be evidence that visual condition affected motor learning.

A second one-way ANOVA was performed for Experiment One to assess if the different training conditions affected post-training performance. The normalized performance during the post-test was the dependent variable with the visual condition during training as the independent variable. If a significant effect was found, a Tukey post hoc test was performed to determine the significance of pairwise comparisons. A significant effect would signify that any changes from the visual condition during training persisted during a full vision post-test.

Experiment Two

A linear mixed model was performed to assess whether visual reliance changed with training. Normalized performance was set as the outcome measure while probe trial block timing (Base, Post, Catch), visual condition, and their interaction were set as the fixed effects and subject was set as the random effect. A significant main effect of probe trial block timing would be evidence that available visual information affected motor performance. A significant interaction between trial and visual condition would be evidence that motor learning affected visual reliance.

Two additional linear mixed models (one for feedback visual reliance and one for feedforward visual reliance) were performed to assess if visual reliance changed directly. Each linear model consisted of either feedback or feedforward visual reliance as the outcome measure while probe trial block timing (Base, Post, or Catch) was the fixed effect and subject was the random effect. A significant fixed effect would signify that motor learning altered visual reliance.

Results

Experiment One: Limiting visual information during training limits performance but not motor learning

Limiting visual information, and in particular feedback visual information resulted in worse motor performance during the training trial blocks. A mixed linear model of performance during the training trial blocks found a significant main effect of trial block number ($p<0.001$) and visual condition ($p<0.001$) on motor performance. The significant main effect of trial block

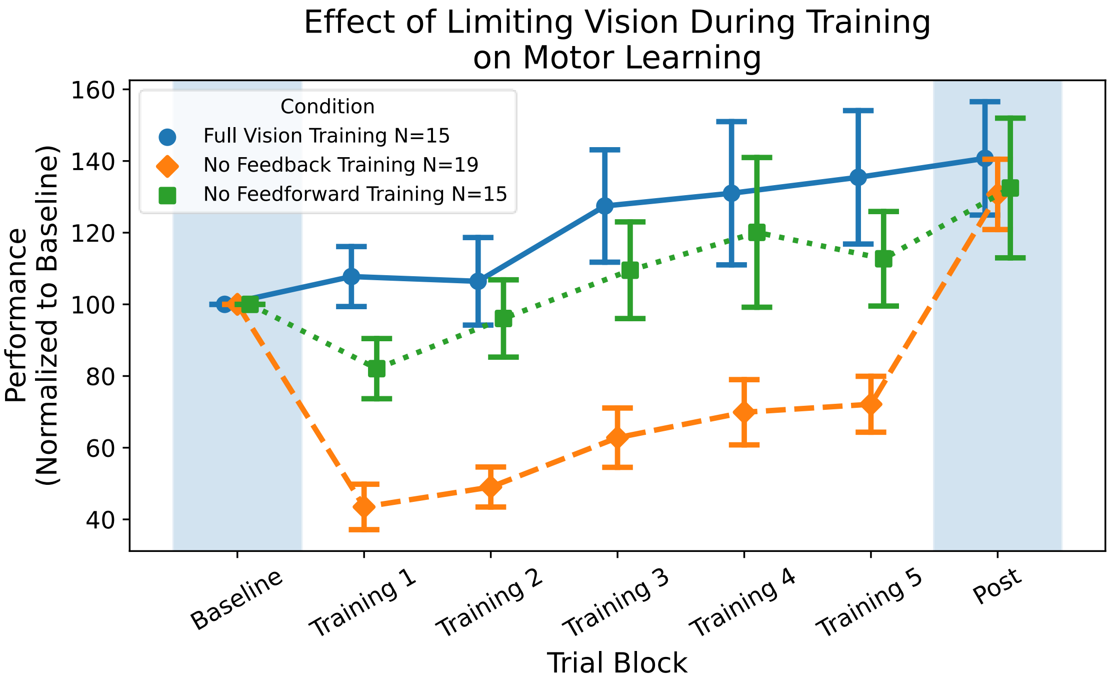

Figure 3-4: Line graph of normalized performance for training in each of the 3 visual conditions. Mean and standard error are shown for each group and during each trial block. Shading represents trials where every group completed the task with full vision.

number supports the hypothesis that participants would improve their performance with practice. A pairwise t-test comparing the visual conditions averaged across training blocks found that performance of the no feedback training group (Figure 3-4, orange) was significantly worse than the full vision (p<0.001) and no feedforward (p<0.001) training groups. The no-feedforward and full vision groups did not significantly differ from each other (p=0.2). This suggests that limiting feedback visual information limits motor performance.

The mixed linear model found no significant interaction between training trial round and visual condition (Figure 3-4, p=0.93). This result suggests that the visual condition did not affect motor learning, as all participants were able to improve at a similar rate (~8/8% improvement per training block). This conclusion was further supported by the results of a one-way ANOVA on the improvement rate which did not find a main effect for visual condition (p=0.87).

Additionally, a one-way ANOVA comparing performance during the post-test did not find a significant effect for visual condition (p=0.88). Taken together the results fail to reject the null hypothesis and suggest that visual condition did not affect motor learning.

Experiment Two: Motor learning reduces visual reliance

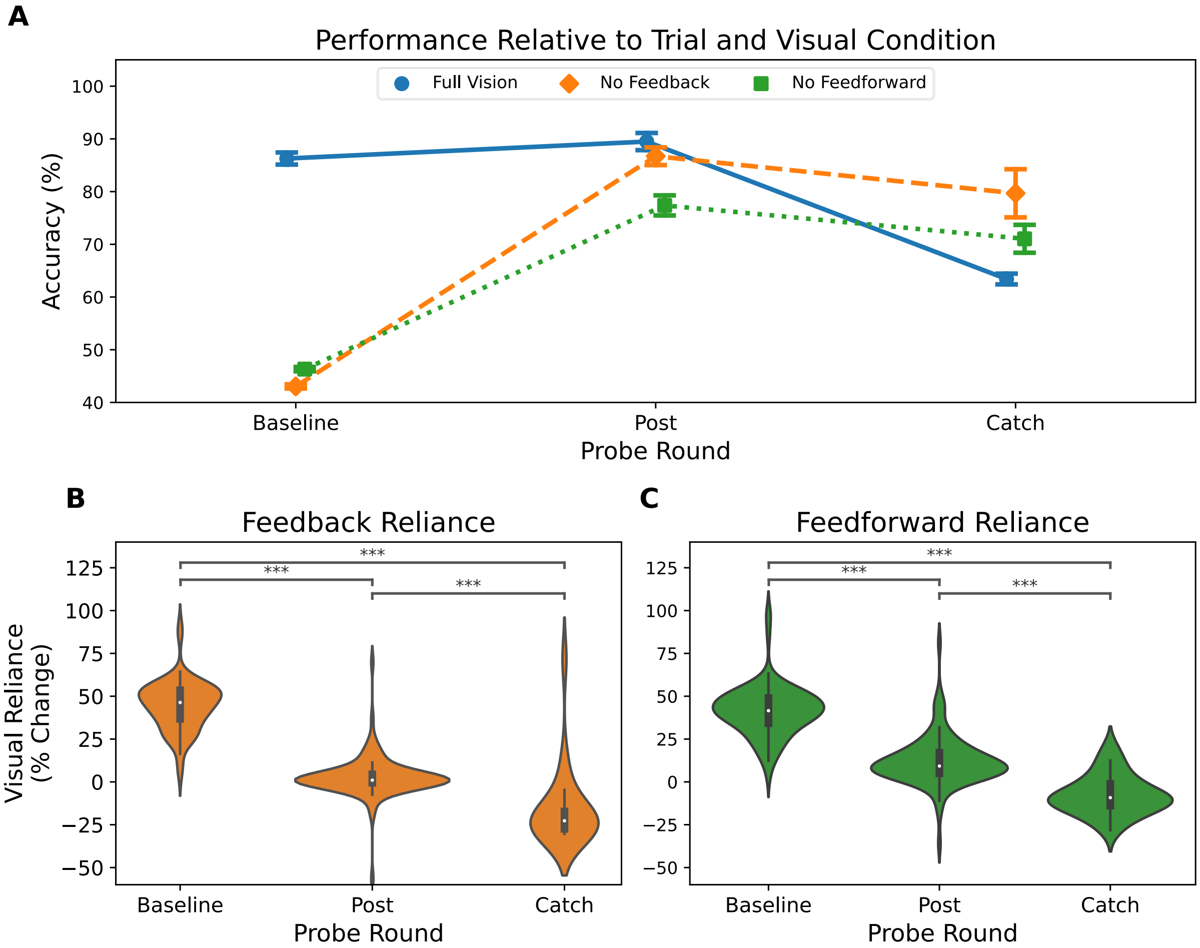

Figure 3-5: A. Line graph of Trial Accuracy during the three probe periods. Each point represents the mean and standard error. B and C. Violin plots of the Feedback (B) and Feedforward (C) visual reliance during the different probe periods. Positive values represent the participant performing worse with limited vision (and thus relying on vision to perform the task). B. The different between the No Feedback (Orange) and Full Vision (Blue) lines in A. C. The difference between the No Feedforward (green) and Full Vision (Blue) in A. *** p<0.001

A mixed linear model found a significant interaction effect between probe round and performance (Figure 3-5A, p<0.001). Participants improved their performance during both limited visual conditions (p<0.001 for each) significantly more than the full vision condition, suggesting a decrease in visual reliance. Pairwise comparisons also found significant improvement in performance with practice ($p<0.001$ in all cases), supporting that individuals did improve their performance with practice.

When we tested visual reliance directly, we found a significant main effect of probe round for both feedback (Figure 3-5B, $p<0.001$) and feedforward (Figure 3-5C, $p<0.001$) visual reliance. A pairwise Tukey test comparing different probe rounds found that visual reliance was significantly different at each time point for both feedback and feedforward visual reliance ($p<0.001$ in all tests). The results of Experiment Two therefore reject the null hypothesis and suggest that motor learning impacted visual reliance.

Discussion

The present paper analyzes the interaction between visual information availability and visuomotor learning using an online, sequence learning task. In Experiment One, participants practiced the task with varying amounts of visual information to assess how visual availability affected motor learning and performance. We found that while visual availability affected motor performance, it did not impact motor learning, either in terms of learning rate or post-test performance. In Experiment Two, we tested participants' visual reliance before and after training with full vision. We found that participants' reliance on both feedback and feedforward visual information reduced with practice. Taken together, the results suggest that people can adapt their motor control strategy to match what visual information is available to them. We will refer to this ability as an individual's visual flexibility. Additionally, this visual flexibility increases with practice, such that participants' reliance on any particular form of vision reduces with practice.

Overall, the results suggest that motor control strategies may shift before any changes in gaze behavior.

Experiment One: Removing visual information reduces motor performance but not motor learning

Experiment One found that the removal of visual information did not affect motor learning, despite reducing motor performance. This is counter to our hypotheses and previous research examining motor learning when visual information was limited (Vieluf et al. 2015; Massing et al. 2016). In our study, while motor learning was not affected when visual information was removed, motor performance was. Unsurprisingly, performing a motor task with less visual information should make the task more difficult, as has been shown in finger coordination (Ariani et al. 2021) and walking (Matthis and Fajen 2014, Timmis and Buckley 2012). However, unlike previous motor learning research (Ballester et al. 2015), the decrease in motor performance when training with reduced vision did not impact motor learning. It may be that learning and executing a movement have different levels of visual flexibility. Motor learning in this simple, sequence learning task may be visually flexible, even if skillfully executing the movement is not. A second explanation may be that participants learned to rely on auditory feedback, which remained constant throughout the task, rather than any visual information. Han and Reber (2022) demonstrated that people can learn sequences in a similar task based on auditory cues alone, although in their task each button had a different auditory tone, unlike the present task. Here, auditory feedback only provided binary feedback on whether the participant was accurate or not. The magnitude and direction of any error was only available through visual feedback and was therefore removed in the no feedback condition. While the auditory feedback alone could not completely replace the visual information, it could provide missing information about response timing. When combined with either limited visual condition to provide visual information about which key to respond with, people could have shifted their performance to rely on the combination of vision and auditory feedback.

While participants demonstrated visual flexibility with learning the sequence, it was not apparent that participants became more visually flexible in their motor performance. Participants did improve their performance regardless of visual condition, however those with limited visual information were never able to compensate for the missing information. These participants only caught up to the full vision training group at post-testing, when everyone had full vision. One explanation may be a disassociation between the sequence pattern recognition and the motor sequence performance. Participants may have been able to recognize the learned sequence visually based on the limited visual information just by watching the screen. However, the limited visual information may have disrupted their ability to time their motor actions accurately. This arrangement would allow for a constant effect of visual condition on motor performance without the visual condition influencing learning the sequence. This would also explain why the three groups performed similarly during the post-test. If all groups similarly learned to recognize the sequence, then when the missing information was returned during the post-test, all participants were able to accurately time their motor actions. The results of Experiment One, therefore, suggest that while vision does affect motor performance during training, it does not impact visuomotor sequence learning, possibly by disassociating sequence learning from motor performance.

Experiment Two: Full vision practice reduces visual reliance and increases performance-related visual flexibility

When we trained motor skill with visuomotor learning in Experiment Two, we found participants became less reliant on visual information with practice. However, rather than a unidirectional shift (with only feedback visual reliance reducing as hypothesized), we found both feedback and feedforward visual reliance were reduced following full vision practice. Previous research has suggested that reliance on vision in general may be reduced with motor learning (Seidler-Dobrin and Stelmach 1998; Guo and Raymond 2010). However, previous research has compared full vision to no vision, rather than the limited visual conditions and reliance examined here. It is interesting that the reduction in visual reliance observed in the current study is general rather than specific to feedback or feedforward visual information. The reduction can be interpreted as participants increasing their visual flexibility to perform the task as they get more skilled. Importantly, unlike in Experiment One, participants visual flexibility was trained in Experiment Two, through the full vision training protocol. It may be that visual flexibility is trained only when participants have a choice of what visual information to use (such as in the full vision condition) rather than when being forced to use one type of visual information. This conclusion has significant implications for future training interventions focused on improving motor performance in limited visual conditions (such as dim lighting or while gaze is focused elsewhere). Instead of guiding a person’s vision, they should be allowed to explore and gather any visual information they deem relevant to improve at the task.

When the learned sequence was removed in the catch trials, we found that participants performed worse on the initial full vision task, but that their performance improved during the subsequent limited vision probe trials. We propose that order effects may be the cause of these results. Specifically, while a new sequence was introduced during the first, full vision catch trial, the same sequence was used for the subsequent limited vision probe trials. Participants may have adjusted to the new sequence during the full vision trial, when they exhibited the expected and characteristic drop in performance following a sequence learning task. Then, when the same sequence was used during the visual probe conditions, participants had already begun learning the new sequence and, with their newly trained visual flexibility and reduction in visual reliance, were able to perform the task better than during the first, full vision catch trial. If this effect remains after randomizing the order of probe rounds in a future study, it may be that as participants reliance on visual information decreased, they reached a point where the visual information is a distraction rather than providing any additional information, in alignment with the specificity of practice hypothesis (Tremblay and Proteau 1998; Proteau and Cournoyer 1990; Kahn and Franks 2004). Future research should look to randomize the order of probe rounds, including the full vision condition.

Limitations

There were a couple of limitations with the present study, in addition to participants being able to rely on auditory feedback and the order of the catch trial probes discussed above. First, while we modulated what visual information was available to participants, we did not track where participants were looking and therefore do not know what visual information participants gathered during the study. It may be that participants only fixated on a subset of the total information, and by tracking where they looked, we may be able to make much stronger and narrower claims on the relationship between vision and motor learning. Second, because participants completed the study online, we did not control the setup of their personal computers.

Variation from different screen sizes and participant seated locations may have changed the perceived visual availability and should be investigated as a possible mediator in the future. Finally, while we tried to remove participants who appeared to not understand the task or who did not participate in good faith, due to the online nature of the study, we cannot be sure that all participants performed the task appropriately.

Conclusions

We conducted two studies to quantify the relationship between motor learning and visual availability. In Experiment One, we found that limiting the availability of visual information reduced motor performance during training but did not impair motor learning. In Experiment Two, we found that participants' reliance on specific forms of visual information decreased with motor learning. Together, the two studies suggest that motor learning affects reliance on specific forms of visual information, but that limiting the availability of visual information does not affect learning. Additionally, participants demonstrated the ability to adapt their motor learning strategies to use any available information which may translate to motor performance following training when visual information is not limited during training.

Acknowledgements

The authors would like to acknowledge Catherine Han for her insight into the experimental design along with all the study participants for their time. This work was supported by the Dr. John N. Nicholson Fellowship, the NIH grant T32 HD101395 Training Program in Sensorimotor Neurorehabilitation, and by Northwestern University's Department of Physical Therapy and Human Movement Sciences.

Chapter 4: Don’t watch your step: Gaze behavior adapts with practice of a target stepping task

Abstract

Vision plays a vital role in locomotor learning, providing feedback information to correct movement errors and feedforward information to inform learned movement plans. Gaze behavior, or the distribution of fixation locations, can quantify how visual information is used during the motor learning process. How gaze behavior adapts during motor learning and in response to changing motor performance is poorly understood. The present study examines if and how an individual’s gaze behavior adapts during a sequence learning, target stepping task. We monitored the gaze behavior of 12 healthy young adults while they walked on a treadmill and attempted to precisely step on moving targets that were separated by variable distances (80%, 100%, 120% of preferred step length). Participants completed a total of 11 trial blocks of 102 steps each. We hypothesized that both mean fixation distance would increase (participants would look farther ahead), and step error would decrease with experience. Following practice, participants significantly increased their fixation distance ($p<0.001$) by 0.27±0.18 steps and decreased their step error ($p<0.001$) by 4.0±1.7 cm, supporting our hypothesis. Our results suggest that early in the learning process participants gaze behavior emphasized gathering visual information necessary for feedback motor control. As motor performance improved with experience participants shifted their gaze fixation farther ahead placing greater emphasis on the visual information used for feedforward motor control. These findings provide important information about how gaze behavior changes in parallel with improvements in walking performance.

New & Noteworthy

People consistently vary how they use visual information to inform walking. However, what drives this variation, and how sampled visual information changes with locomotor learning is not well understood. Here, we find that gaze fixation locations moved farther ahead while step error decreases as participants practice a target stepping task. The results suggest participants increasingly used a feedforward locomotor control strategy with practice.

Introduction

Vision plays a vital role in controlling human walking. Visual information is a primary source of feedback information, to ensure the safety and accuracy of the current step, and an important input for feedforward motor planning, to efficiently prepare and execute future steps. Gaze behavior, or the distribution of visual fixation locations, is one way to quantify how visual information is used during walking. Gaze fixations close to the location where the viewer steps on the ground can guide swing limb movement and precision foot placement (Patla 2003). When these close fixation locations are occluded or ignored, foot placement becomes more variable, reducing postural steadiness (Koren et al. 2021) and making foot clearance of obstacles (such as a curb) less likely (Timmis and Buckley 2012). In contrast, fixations farther ahead are used to plan the immediate and upcoming steps and to confirm that one is walking towards their desired destination (Patla and Vickers 2003, Hollands et al. 2002). When the ability to look ahead is removed, individuals make a series of discrete segmented movements, rather than a single continuous movement, to account for obstacles in their path (Saeedpour-Parizi et al. 2020; Yamamoto et al. 2019). Thus, motor performance during walking is intricately related to the gaze behavior that dictates the availability of visual information.

An individual’s preferred fixation distance is updated depending on individual motor skill level and the challenges presented by the specific walking task. With normal vision, healthy adults walking on smooth, level surfaces fixate ~2 steps ahead, though they will glance towards their feet and farther ahead to gather additional information (Patla 2003; Matthis et al. 2018). When walking across rough terrains, (such as stepping across rocks (Matthis et al. 2018) or uneven cobblestones (Thomas et al. 2020)), where precise foot placement is required to maintain stability, individuals decrease their focus to ~1.2 steps ahead (Matthis et al. 2018). This shift appears dependent on the task requirement to precisely place the foot in a specific location. In more challenging terrains, there is a larger decrease in mean fixation distance, suggesting the role of visual information shifts to emphasize feedback motor control (Matthis et al. 2018). Similarly, older adults (Chapman and Hollands 2010), individuals with an incomplete spinal cord injury (Malik et al. 2017), and individuals with developmental coordination disorders (Warlop et al. 2020) all display gaze behavior fixations that are closer to their feet when compared to young and unimpaired counterparts. Here this reduction in gaze fixation distance is likely to ensure safe and accurate foot placement. In contrast, elite athletes, who are less likely to require visual feedback to ensure safe foot placement and perform their practiced skill, tend to look farther ahead - a strategy that emphasizes motor planning and may improve the energetic efficiency of their movement (Piras et al. 2010). Collectively, this research suggests that fixation distance adapts to both the demands of the task and individual motor skill level.

Gaze behavior can also be quantified using the timing of fixations relative to actions. Specifically, the window of time when a person gathers visual information for the desired destination of a movement (i.e., first and last fixations on a given target) can be compared to the associated window time of the directed movement (i.e., the swing phase of a single step onto the target). By comparing the start of these two time-windows, we can estimate how far ahead in time an individual is gathering visual information to plan their movement. The earlier the individual begins gathering information on the target location, the more feedforward visual information is available to guide the motor planning to step on that target. In addition, by comparing the end of these two time-windows, we can estimate how much visual feedback was required to complete the movement. Visual information gathered after the movement is completed would indicate an emphasis on feedback information as the participant watched the foot contact the target. These fixation timing metrics have been shown to change based on the predictability of the environment and the importance of precise foot placement (Domínguez-Zamora et al. 2018). Specifically, and in line with fixation distance, when the environment is more predictable the visual information window shifts earlier in time compared to the movement window (suggesting an increased emphasis on feedforward motor control). When the task requires precise foot placement, the opposite occurs with individuals shifting their visual information window to overlap more with the movement window (suggesting an emphasis on feedback motor control). As with fixation distance, we see that fixation timing also adapts to the demands of the task.

How do these differences in gaze behavior between populations and walking tasks develop? If the changes in fixation distance and timing are a part of the motor learning process, then we would expect gaze behavior to update in a manner consistent with general motor learning theory. Specifically, during the learning process motor control strategies shift from a reliance on feedback motor control to a feedforward motor control strategy (Franklin and Wolpert 2011, Franklin et al. 2003). Such a progression has been found when learning to walk (Yamamoto et al. 2019), catching a ball (Hayhoe et al. 2002), and shooting a basketball (Oudejans et al. 2002).

With practice of a novel task, we would expect gaze behavior to mirror this shift, gathering fixations close to the movement early in the learning process and shifting farther ahead as the individual shifts to a feedforward motor planning strategy. However, whether gaze behavior follows this pattern remains unclear. While several studies find gaze behavior to shift farther ahead when learning reaching or finger coordination (Perry et al. 2020; Vieluf et al. 2015; Sailer et al. 2005; Ariani et al. 2021), others find no change in fixation distance (Mathew et al. 2019). In walking, the evidence is more mixed. Kopiske and colleagues (Kopiske et al. 2020) found short-term increases in fixation distance with practice, but that these changes did not persist over the medium- or long-term despite repeated practice. Koren and colleagues (Koren et al. 2022) found fixation distance decreased with practice, though their study lacked specificity in fixation distance compared to previous literature.

The present study, therefore, aimed to better understand if and how gaze fixation distance and timing changes during locomotor skill acquisition. To evaluate this question, we directly measured gaze fixation distance and timing as healthy individuals practiced a challenging precision stepping task. To maximize the learnability of the task (and therefore maximize changes in motor skill), a repeating sequence of stepping targets separated by variable distances (80%, 100%, 120% of preferred step length) was embedded into the precision stepping task. Choi and colleagues (Choi et al. 2016) have shown that people can learn a repeating sequence of step lengths through sequence learning mechanisms as evidenced by a decrease in performance when the learned sequence is removed. We hypothesized that with practice performing the target stepping task, an individual’s mean fixation distance would increase (move farther ahead of the body) and step error (the distance between the foot and the target) would decrease. In addition, we anticipated that this shift in fixation distance would be accompanied by a shift in fixation timing, with the visual information window shifting earlier in time compared to the movement window, emphasizing feedforward locomotor control strategies. The hypothesized results would be indicative of increased emphasis on feedforward fixations as locomotor skill improves. To further strengthen the result, we included a catch trial during which the target sequence was removed. If the changes in fixation distance are related to sequence learning, then removing the sequence should temporarily reverse any changes in step error and fixation distance, providing additional evidence towards how locomotor performance and gaze behavior are intertwined.

Materials and Methods

Participants

12 healthy young adults provided written informed consent and participated in the study. All procedures were approved by the Northwestern University Institutional Review Board. All participants were screened via self-report to ensure they had normal or corrected-to-normal vision and did not have any current neuromuscular or musculoskeletal injuries known to affect their balance or gait. Demographic Information available in Table 4-1.

Table 4-1: Demographic Information

N	**12**
Age (years)	22-31
Sex	8 Women, 4 Men
Height (meters)	1.74 ± 0.10
Step Length (meters)	0.52 ± 0.07

Experimental Setup

Task environment. Participants were asked to walk on a treadmill and step on a series of moving targets that were streaming towards them. All walking occurred on an oversized treadmill (3 m x 1.5 m, TuffTread, USA). A static board was placed level with the front of the treadmill belt to extend the target viewing space to 4 m x 1.5 m (board + treadmill belt). Stepping targets (7 cm x

15 cm) were projected using an overhead projector (Hitachi, Japan) onto the target viewing space.

Motion Capture: We collect 3D kinematic data during walking to quantify foot and head movement. Specifically, we used a 12-camera optical motion capture system (Qualisys, Gothenburg, Sweden) to collect walking kinematics and quantify real-time stepping behavior. We placed thirteen passive reflective markers on each participant to track their motion throughout the duration of the trial. Three non-collinear markers on the head-mounted eye tracker determined the headset viewing plane relative to the lab reference plane. The other 10 markers tracked the 2nd, 3rd, and 5th metatarsals, the lateral malleolus, and the calcaneus of each foot to determine locations of the two feet.

Eye-tracking. Pupil locations were tracked throughout the study to determine gaze behavior and fixation locations. To capture gaze behavior, participants wore a head-mounted eye tracker (Pupil Core eye tracker, Pupil Labs, UK). The headset uses IR reflection to determine the 2-dimensional pupil location of each eye, and, following a calibration period, we transformed this data into a 2-dimensional gaze point in the viewing plane. Gaze vectors were then determined using methods described in (Matthis et al. 2018), from which fixation points were defined as the location where the gaze vector intersected with the treadmill surface.

Stepping Task

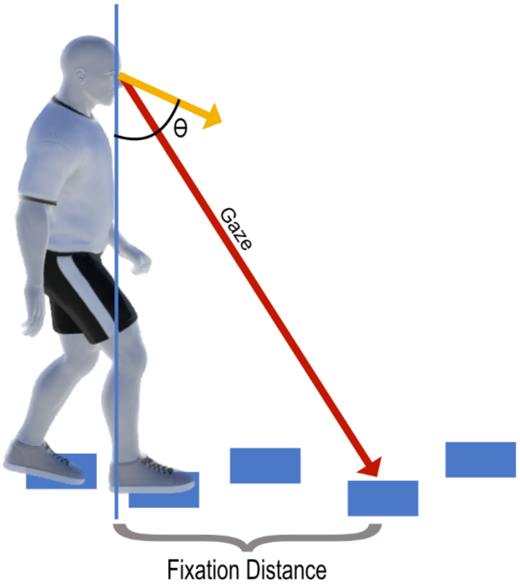

Figure 4-1: Diagram demonstrating the stepping task with head angle (theta) and fixation distance measurement.

During the stepping task, participants walked on the treadmill while stepping targets were projected onto the treadmill (Figure 4-1). Stepping targets were projected onto the treadmill surface with a set step width (matched to participant's preferred step width) and variable step lengths of short (80% of preferred step length), preferred, or long (120% of preferred step length) steps. Each trial consisted of 102 targets to step on. Participants were instructed to step on the projected targets as accurately as possible and received auditory feedback (error noise) when the foot was too far (greater than 0.2 m) from the target. The Stepping targets were projected such that they moved faster than the treadmill belt speed (two times the speed of the treadmill). During piloting, participants performed near ceiling during baseline (greater than 90% accurate) when the speed of the targets was matched to the treadmill speed. Increasing the speed of the targets mitigated the ceiling effects and provided participants with room to improve with practice.

Experimental Protocol

Participants first completed a series of calibrations. An eye tracker calibration, consisting of the participant fixating on static targets projected onto the treadmill surface, was used to calibrate participants' gaze vectors. A standing calibration determined the flatfoot height of the calcaneus marker. During walking trials, we defined real-time heel strike as the time when the calcaneus marker dropped within 5 mm of the participant's flatfoot height. Participants also completed a 2-minute walking trial on the treadmill (no targets) to determine their preferred step length and step width that would be used to define the spacing of targets during the experimental trials. All walking trials were performed at a fixed speed (0.9m/s) for all participants. People naturally walk slower during target stepping protocols and so the speed was chosen to allow participants to comfortably perform the task and have enough time for both feedback and feedforward locomotor control strategies while still challenging participants enough to avoid ceiling effects.

Following these calibrations, participants first completed a baseline (102 stepping targets) trial of the stepping task during which the order of the target step lengths was randomized. Following baseline, participants completed 5 sequenced trials, then a catch trial, and finally 4 more sequenced trials. During all sequenced trials, the targets appeared in the same, repeating, 6-step pattern (specifically all participants experience the following pattern of step lengths which always started with their right foot: 120% - 120% - 80% - 120% - 100% - 80%) to encourage sequence learning and accelerate overall motor learning within the duration of the experiment. A catch trial (during which the targets were presented in a random order of step lengths, though this specific sequence order was consistent across participants) was included to determine whether the learning was specific to the repeating sequence or generalized to the target stepping task. Choi and colleagues (Choi et al. 2016) demonstrated sequence learning in a similar stepping task with targets projected on a screen in front of the participant rather than directly onto the ground. Participants were given the option of taking self-paced breaks in between trial blocks, however, most participants continued walking on the treadmill for the duration of the experiment.

Data Analysis and Processing

Motion capture data: Following manual marker correction in Qualisys Tracking Manager software, data was exported and processed through a custom Python (v3.8) script. Specifically missing marker data (less than 10% of individual marker data) was interpolated using a cubic interpolation through the pandas python package. After interpolation, the entire trajectory was passed through a 6 Hz low pass filter (Winter, Sidwell, and Hobson 1974).

Eye tracking: A post hoc calibration and gaze mapping were performed using pupil player software before being exported to a custom Python script. The x and y position of each pupil and of the normalized gaze position on the visual plane were filtered as follows: First, the most extreme values (top and bottom 5%) were masked to remove mischaracterizations of the pupils. The data was then interpolated to the nearest point and finally a median filter with a window size of 10 samples was applied. Saccades were defined as any time an eye's pupil position changed between aligned frames (100hz) more than 0.15 mm (~70 deg/sec) in the x direction or 0.3 mm (~140 deg/sec) in the y-direction. Additionally, any gaze point with lower than 60% confidence (as calculated by Pupil Labs) was discarded. To determine the fixation point, we followed the methodology described by Matthis and colleagues (Matthis et al. 2018). Specifically, we created gaze vectors originating at the scene camera of the eye tracker and connecting through the fixation point provided by Pupil Labs on the recorded scene camera image. That image was arbitrarily defined as residing on a rectangle 1 meter in front of the scene camera. The corners of the rectangle were defined by the intrinsic camera values (103 degrees horizontal and 54 degrees vertical) and the center was located 1 meter in front of the scene camera and normal to the head vector originating at the scene camera. The fixation point on the scene camera image was placed on this rectangle and a gaze vector from the scene camera and through the fixation point was computed. The gaze vector was then projected to intersect with the treadmill plane to determine the fixation point (Matthis et al. 2018).

Projected target locations: The location of projected targets was determined by linearly mapping the projection space into the motion capture system space. A unique linear mapping was created for each participant to ensure data quality.

Data Alignment: Data between the target locations and motion capture were sampled at 100hz and aligned using the motion capture system frame numbers which were streamed in real-time to the MATLAB program recording and projecting the targets. Gaze data were sampled at 200hz and aligned to the motion capture system data by aligning the nearest timestamps.

Outcome measures

Step error: Step error was determined as the Euclidean distance between the center of the foot defined by the 5 reflective markers on each foot) and the center of the target on the plane of the treadmill.

Fixation distance: Fixation distance was defined as the Euclidean distance between the center of the headset (blue line on Figure 4-1) and the treadmill surface fixation point along the plane of the treadmill (Figure 4-1).

Look ahead time: Look ahead time was defined as the time it would take a participant’s foot to reach the location being fixated upon. In practice, look ahead time is equal to the fixation distance divided by the treadmill speed (0.9 m/s).

Head angle: In addition to fixation distance, we recorded head angle. While a participant's head angle is accounted for in fixation distance, head angle has historically been used to approximate fixation distance. By including it here, we both allow for historical comparisons and provide additional validation for fixation distance as head angle data is less processed and more reliable than gaze location. Head angle was therefore defined by the vertical angle between the normal vector to the headset viewing plane and the vertical z-axis (Figure 4-1).

Toe off interval: The toe-off interval is defined as the time (in seconds) between the start of the first fixation onto a target and the toe-off of the foot which will step onto that target. A fixation which begins before toe-off is coded as a negative interval while a fixation after toe-off is coded as a positive interval.

Heel strike interval: The heel strike interval is defined as the time (in seconds) between the end of the last fixation on a target and the heel strike of the foot onto that target. A fixation which ends before heel strike is coded as a negative interval while a fixation after heel strike is coded as a positive interval.

Statistical Analysis

For all analyses, the first 6 targets of a trial (the first complete presentation of the sequence) were removed to allow participants to align their gait pattern with the phase of the stepping targets.

The remaining 96 steps were analyzed for each participant. Significance was set at $p < 0.05$ for all analysis unless otherwise specified.

For fixation-based metrics, we analyzed the distance, toe-off interval, and heel-strike interval, of on treadmill fixations. Off treadmill fixations, which accounted for ~10% of the data, were considered irrelevant for this analysis. Fixation distance was grouped by step such that each step's average fixation was equal to the mean fixation distance of all fixation samples during the step's swing phase. A mixed linear model, with trial number as a fixed effect and subject as a random effect, was used to calculate the change trial-to-trial in fixation distance, toe-off interval, and heel-strike interval. Given a significant main effect of trial on each outcome measure, pairwise t-tests or Mann Whitney U tests (depending on a normality check using the Pingouin Python package) with a Bonferroni correction were completed between baseline and the final trial (trial 9), to determine if participants significantly changed with practice, and between the catch trial, and the trials immediately before and after the catch trials (trials 5 and 6 respectively) to determine if the changes were specific to sequence learning or more general task learning.

In addition to the between trial analysis, we conducted a within-trial analysis. Specifically, a Mixed Linear Model was used to examine if participant fixation distance changed on steps following an accurate vs inaccurate step (when they would be reacting to the auditory feedback). Given a significant effect, a post-hoc analysis was completed to compare fixation distance and step error between the first and last accurate step in a series of consecutive correct steps.

Results

Representative Participant

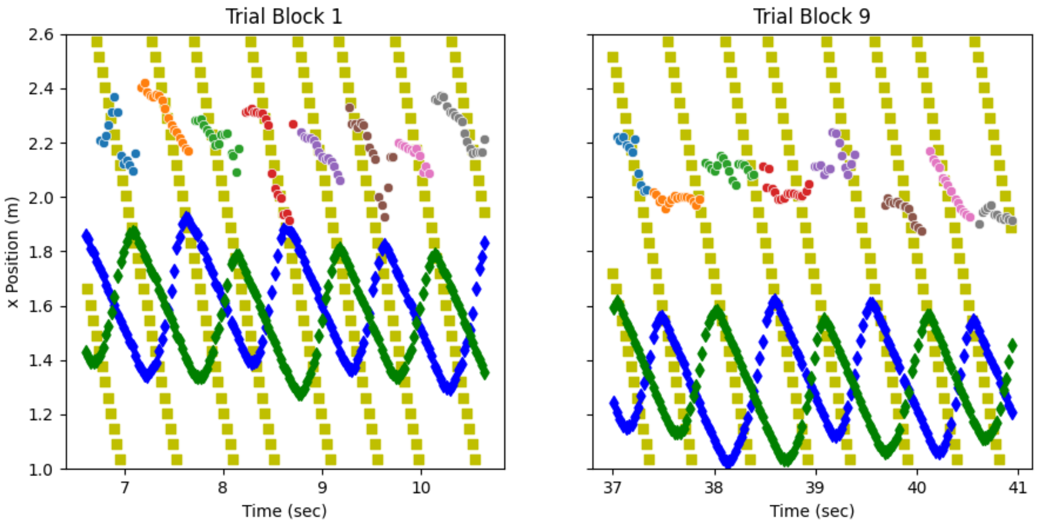

Figure 4-2: Data from one participant of the anterior-posterior position of the left (blue diamonds) and right (green diamonds) heel, stepping targets (yellow square) and gaze location (colored dots, each color grouping is a unique fixation) through time. The figure demonstrates the hypothesized shift in fixation distance with practice as gap between the colored fixation dots and the heel diamonds is larger in the after practicing the task (on the right).

Processed data showing the locations of the left and right feet, the stepping targets and the fixation point on the treadmill are presented in Figure 4-2. We can see the participant fixating onto a target and tracking its movement before saccading to the next target and beginning a new fixation. The participant also demonstrates the expected shift forward in fixation distance between the early and late sequenced trials.

Step Error and Fixation Metrics Change with Practice

With practice, participants decreased their step error, and increased their fixation distance, and head angle (Figure 4-3). A mixed linear model found a significant main effect of trial on fixation distance ($p < 0.001$), head angle ($p < 0.001$), and step error ($p < 0.001$). When comparing the

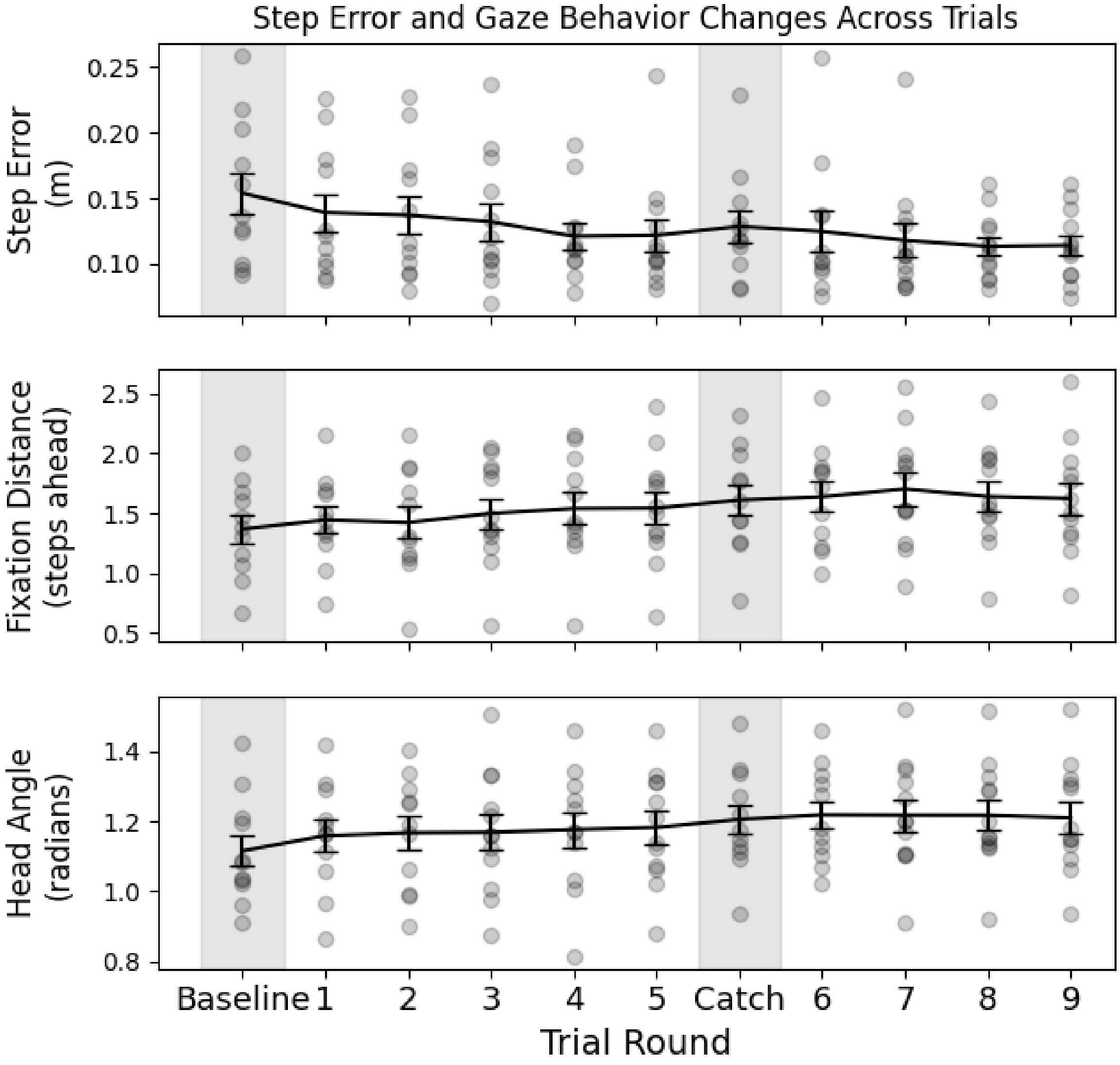

Figure 4-3: Error bar plots of mean step error (top), fixation distance (middle) and head angle (bottom). Datapoints represent individual participant averages. Shaded vertical bars indicate trials when there was no repeating sequence. Error bars represent SEM. Results support step error decreasing while fixation distance and head angle increase (the participant looks farther ahead) with practice.

baseline vs. the last trial, we find a significant difference for step error (Mean Difference = -4 cm, $p < 0.001$, hedges g = 1.33), fixation distance (Mean Difference = 0.27 steps ahead, p = 0.003, hedges g = 0.62), head angle (Mean Difference = 0.09 radians). Participants increased their average look ahead time from 1.51 seconds to 1.80 seconds (290 msec total change). When

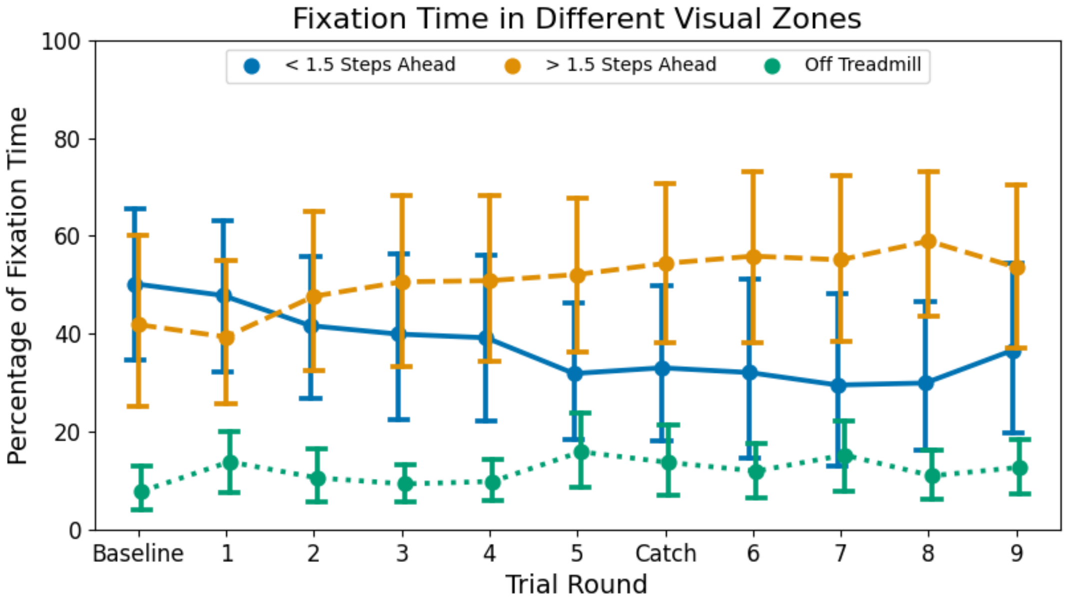

Figure 4-4: Error bar plot represent the percent of fixations directed towards less than 1.5 steps ahead (blue, solid) greater than 1.5 steps ahead (orange, dashed) or off the treadmill (green, dotted). Error bars represent 95% confidence intervals. Results demonstrate an increased fixation time towards information greater than 1.5 steps ahead with practice, but that the participant consistently fixates in all three visual zones.

looking at where individuals direct their gaze, we found that with practice, more fixation time was directed farther ahead (greater than 1.5 steps ahead) (Figure 4-4). The number of fixations directed off the treadmill surface remained relatively consistent, suggesting that foveal vision was consistently relied upon for the task.

For fixation timing metrics, a mixed linear model found a significant main effect for the heel-strike interval (p = 0.008), but not for the toe-off interval (p = 0.051). We did not find a significant difference between baseline and the last trial for heel-strike interval (Mean Difference = -0.02 seconds, p = 0.49).

Changes were driven by general task learning rather than sequence learning

A Tukey post hoc test was performed to compare the trials before and after the catch trial with the catch trial. The catch trial did not significantly differ from the adjacent trials in step error (p =

0.8 for both), fixation distance (previous trial $p = 0.3$, next trial $p = 0.7$), or head angle ($p = 0.4$ vs previous and next trials).

Participants significantly changed their fixation distance following an error step

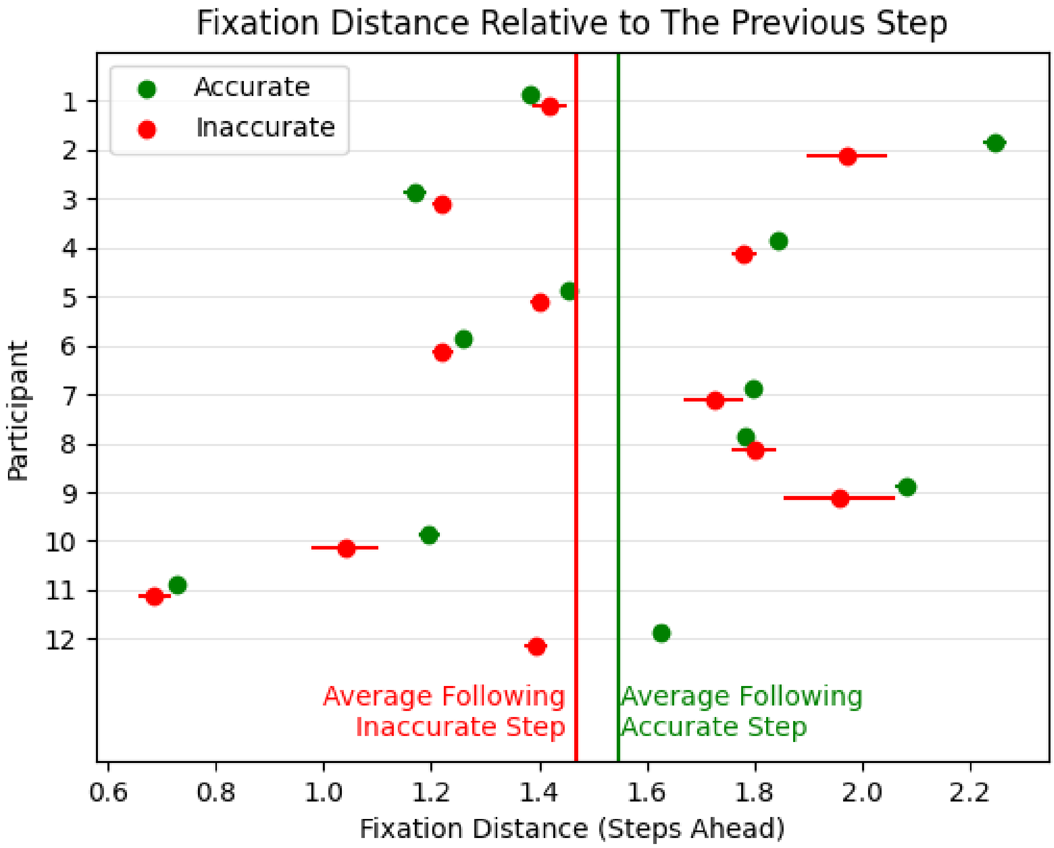

Figure 4-5: Mean and SEM of each participants' fixation distance during the step following an accurate (green) or inaccurate (red) step. Vertical lines represent group means with each subject having equal weighting. On average, participants shifted their gaze closer to themselves following an inaccurate step.

To determine how participants respond to an error step, a mixed linear model with subject as a random effect and previous step accuracy as a fixed effect was performed to compare the fixation distance of a step following an error or accurate step. A significant change in fixation distance based on the previous step accuracy ($p < 0.001$) was found with an error on the previous step leading to a mean reduction in fixation distance of 0.08 steps (Figure 4-5).

Participants did not exhibit learning within trial rounds

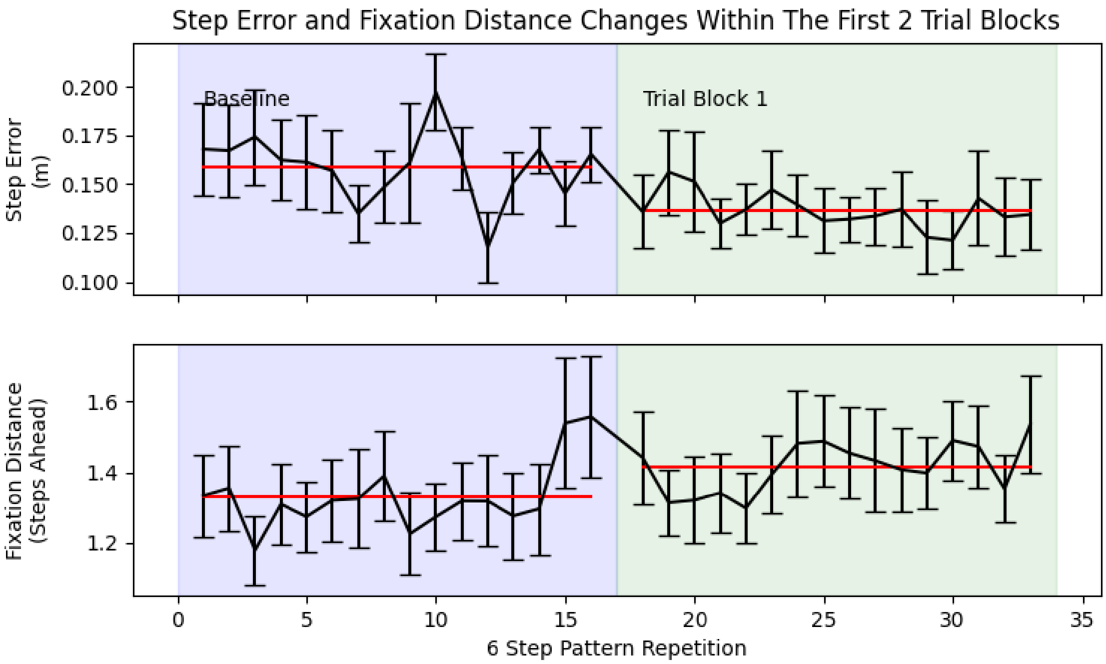

Figure 4-6: Changes in step error (top) and fixation distance (bottom) for the first 2 trial blocks (baseline shaded blue, trial block 1 shaded green). Horizontal red lines represent mean values across the entire trial block (each shaded region). Error bars are SEM. The results support the changes occurring between trial blocks (red lines) and less so within trial blocks (error bar plots).

While participant step error and fixation distances changed across trial rounds, the changes may be occurring on a smaller time scale such that a gradual shift occurs constantly within trial rounds. Because participant fixation distance did change following a step error, within-trial changes were compared based on the first and last accurate step in a streak of accurate steps in a row (minimum streak length of 3 steps). A Mann Whitney U test found a statistically significant difference in step error ($p < 0.001$, Mean Difference = 1 cm) but not in fixation distance ($p = .96$).

Additionally, given the large change during the initial trial blocks, a post hoc examination comparing the change in step accuracy and fixation distance was conducted between the baseline and trial block 1 (Figure 4-6). To allow for any learning effects while minimizing the effect of step error, performance was grouped in 6 step repetitions representing a complete loop through the sequenced pattern (for trial block 1). A mixed linear model with trial (baseline and trial block 1) and pattern repetition (1-16) as fixed effects and subject as a random effect was conducted for outcome measures step error and fixation distance. Trial ($p < 0.001$) but not pattern repetition ($p=0.21$) had a significant fixed effect on step error, while both trial ($p = 0.001$) and pattern repetition ($p < 0.001$) had significant fixed effects on fixation distance (Figure 4-6). Despite the significant fixed effects, a Mann Whitney U test did not find a statistically significant difference between the first and last pattern repetition for fixation distance during these 2 trials ($p = 0.06$).

Discussion

The present study examined how gaze behavior changed in relation to motor learning during a sequence stepping task. Participants were instructed to step on projected targets as accurately as possible while their gaze behavior was monitored. The results support our hypothesis that both fixation distance would increase and stepping accuracy would improve with experience. This shift in fixation location did not impact fixation timing, as participants toe-off and heel-strike intervals did not significantly change with practice. Despite this, we found participants made concurrent reductions in their step error and increases in their fixation distance between trial blocks. Participants updated their gaze behavior in a manner that suggests they updated locomotor control strategies with practice, increasing their emphasis on feedforward motor planning. Overall, the results support that fixation distance increases with locomotor learning.

Our primary finding was that gaze fixation distance increased with practice. As expected, with experience participants shifted their gaze to sample visual information that was farther ahead.

This increase in average gaze fixation may have been related to individuals increasing their emphasis on feedforward motor control strategies. Previous literature has established that general motor learning is accompanied by a progression from feedback to feedforward motor control strategies (Franklin and Wolpert 2011). By shifting their gaze fixation, individuals change what sensory (and in particular visual) information is available to perform the task. Fixations close to the individual benefit online reactive control strategies, providing information about where the limb and current step target are and allowing immediate corrective actions to be taken as needed. Fixations farther ahead benefit motor planning by providing more information about the future and providing additional time to process the information, allowing the individual to create and execute efficient motor plans.

Participants shifting their gaze farther ahead is in line with previous upper limb (Sailer et al. 2005, Perry et al 2020) and walking (Kopiske et al. 2020) studies where participants shifted their gaze farther ahead with practice. The shift is likely accompanied by a de-emphasis on feedback and an increased emphasis on feedforward motor control strategies (as suggested by Sailer et al. 2005). However, as demonstrated in Figure 4-4, participants are always performing fixations both less than 1.5 steps ahead (to provide feedback on the current step) and greater than 1.5 steps ahead (to provide information for feedforward planning of future steps). Participants therefore use a combination of feedback and feedforward motor control to walk efficiently (similar to driving Lehtonen et al. 2013). The changing fixation distance and locomotor control strategies may alternatively suggest an increased planning horizon (Ariani et al. 2021, Bashford et al. 2022). Under this interpretation, practiced participants are better able to use visual information from farther ahead, possibly due to more efficient processing of feedback visual information. Unlike an overall shift in locomotor control strategy, this perspective would suggest that participants remain just as reliant on feedback motor control but are able to achieve any corrective actions with shorter fixation periods (and therefore less visual information to guide feedback control). Our results also support this alternative and future research where visual information is occluded periodically throughout the locomotor learning process would be necessary to tease these two hypotheses apart.

Surprisingly, changes in fixation location with practice did not impact fixation timing. Rather than shifting the entire fixation window farther ahead and therefore earlier relative to toe-off and heel-strike, participants maintained a consistent timing of when they began and finished looking at a target. Instead, participants changed where they directed their gaze between those two timepoints (i.e., during swing phase). As depicted in Figure 4-4, while participants did spend more time looking farther ahead, they did not stop performing fixations back to the current step (less than 1.5 steps ahead). Therefore, participants may have shifted their gaze farther ahead in terms of distance for the majority of swing phase, but still made a confirmatory fixation back at their foot to confirm accurate foot placement. It may be that participants became more efficient confirming where their foot is in space (in line with the possible shift in planning horizon) or that they became more proficient at using peripheral vision to guide target stepping (as seen during reaching by Perry et al. 2020). Either change would allow participants to look farther ahead without reducing their ability to perform a feedback-driven motor control strategy.

When the learned sequence was removed, participant motor performance and fixation metrics did not significantly change. While we expected both to revert towards baseline levels, the lack of any change suggests that the motor learning across the entire study was due to general task learning (learning to step accurately on targets) rather than sequence learning impacting performance as we expected. The main takeaway here may have more to do with the task design. Unlike Choi and colleagues (2016), we projected our stepping targets directly onto the treadmill, rather than presenting them on a screen in front of the participant. It is possible that the sequence is more recognizable when presented on a screen as the visuomotor mapping between the participant's stepping and the screen representations recruits more cognitive resources compared to the more natural guidance of their foot to a seen target on the ground (treadmill belt) employed in our study. While most participants could tell that the prescribed step length changed, few were able to articulate the pattern, even after 153 repetitions. Additionally, the speed of the targets and the sequence employed in the present study were different than in Choi and colleagues, though performance characteristics such as participants having more difficulty with short steps compared to preferred or long steps and the percentage of accurate steps improving from ~30% to ~60% is comparable to the results of Choi and colleagues. We therefore suspect that the modified task design may have impaired participant pattern recognition and therefore limited any sequence learning effect.

On a step-by-step basis, gaze behavior did not change significantly relative to stepping performance. The main trigger for sudden changes in gaze behavior came from the motor errors/auditory feedback, with fixation distance reducing on average 0.08 steps immediately following an error step, though there was large intersubject variability. The variability may suggest that different participants had different strategies to deal with errors. Some participants largely maintained their gaze behavior while others exhibited large changes following an error step. Neither a participant's percentage of accurate step (which would suggest an acclimatization to the error noise) or overall fixation distance (which would speak to different locomotor strategies) appear to be related to the intersubject variation. Future research is needed to disentangle the significance of variability. Accepting that participant fixation distance does systematically reduce following a step error (as the data suggests), the change following an error step brings up the question of causality. Specifically, since participant gaze behavior changed following an error step, the step error may have triggered the change in fixation distance. This behavior has a real-world parallel where people look down following a stumble to maximize visual feedback and regain their balance. While participants exhibited similar behavior, a follow-up study is needed to determine whether the fixation change was due to the step error (representing a bottom-up, movement driven response) or a reaction to the error auditory feedback (creating a top-down, goal-directed response).

The reduction in fixation distance following a step error also provides a possible alternative explanation to the main result of fixation distance increasing with practice. Given that participants performed fewer errors with practice, it is possible that the trial-by-trial change in fixation distance was due to fewer errors (and therefore fewer temporary reductions in fixation distance) rather than a change in visuomotor control strategy. To check this, we reran the mixed effects models removing the step following an error step from the dataset. Again, we found participants significantly increased their fixation distance with practice ($p < 0.001$) and decreased their step error ($p < 0.001$) with practice.

When we look at streaks of correct steps (to remove any “reset” in fixation distance from a step error), we do not find a significant change in fixation distance and while step error does increase, the size of the increase (~1cm on average) is so small that it is unlikely to be clinically relevant. Similarly, when we zoom in on the first two trial blocks (baseline and sequenced trial 1) we do not see a significant change in step error within the trial block. While we do see a significant slope for fixation distance within the first 2 trials, we do not see a significant difference between the beginning and the end of a trial block. When we combine this lack of within-trial-blocks changes with the significant differences found between trial blocks, the results suggest some form of consolidation is necessary to update gaze behavior. This contrasts with the findings of Kopiske and colleagues (Kopiske et al. 2020) who found that participants adapted their gaze behavior in response to simulated stepping hazards (icy patches) within trial blocks, but any adaptations did not carry over between trial blocks. One reason may be the continuous nature of the present task with a target for every footfall here vs. one target every few steps in Kopiske et al. 2020. Given this difference, the present study is more in line with reaching (Perry et al. 2020) and finger coordination (Sailer et al. 2005) studies, where participants had a continuous task to respond to and shifted their gaze to sample information farther ahead as they practiced the task. Our current results suggest that time between tasks may be necessary to consolidate learning and update gaze behavior.

There are a few limitations with the present study, outside of those mentioned earlier. The primary limitation is that while the present study measured where individuals look, it did not quantify any cognitive processing being done with that information. While it is likely that processing follows foveal vision, this is not a requirement (Perry et al. 2020). Stepping behavior is often relatively automatic and therefore gaze may be directed for other purposes (such as looking at someone while you talk to them). A follow-up study should assess how the processing of visual information changes with locomotor learning by measuring how performance changes when visual information is removed from different areas. Such a study would also help differentiate between a shifting motor control strategy and an increased cognitive flexibility associated with an increased planning horizon discussed earlier. A second limitation is the lack of updating difficulty in the task. Research has suggested that motor learning is maximized by progressively adapting task difficulty to match an individual's motor skill level (Wilson et al. 2019). To consistently compare gaze behavior to task performance, we did not update task difficulty as participants improved. While this was necessary to create a consistent comparison point, it is possible that changes in gaze behavior were due to reasons other than improved motor skill, such as participant boredom. A follow-up study with updating task difficulty based on performance may be able to better understand why gaze behavior is updated in the manner seen in the present study.

Overall, the results of the present study suggest that gaze behavior updates with changes in motor skill. Specifically, we found that with practice of a novel locomotor learning task, mean fixation distance increased, and step error decreased. However, these changes were only detectable between trial blocks and not on a step-by-step basis. The results suggest that changing gaze behavior is an integral part of locomotor learning, allowing individuals to emphasize different motor control strategies by providing different visual information. However, we found that the timing of fixations did not change with practice, suggesting individuals may be changing how they process visual information along with changing what visual information they collect. Future research should therefore investigate how the cognitive processing of visual information changes with locomotor learning.

Acknowledgements

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Chapter 5: Seeing does not mean processing: Where we look and the visual information we rely on change independently as we learn a novel walking task

Abstract

People use vision to inform motor control strategies during walking. With practice performing a novel target stepping task, people gradually shift their gaze farther ahead, transitioning from watching their feet contact the target to looking for future target locations. The shift in gaze focus suggests the role of vision in motor control changes from emphasizing feedback to feedforward control. The present study examines whether this change in visual fixation location is accompanied by a similar change in reliance upon visual information. Twenty healthy young adults practiced stepping on moving targets project on the surface of a treadmill. Periodically, participants' visual reliance was probed by hiding the stepping targets when they would inform feedback or feedforward (targets < or > 1.5 steps ahead, respectively) motor control strategies. We calculated visual reliance as the increase in step error when targets were hidden compared to being fully visible. We hypothesized that with practice, participant reliance on feedback visual information would decrease and their reliance on feedforward visual information would increase. Contrary to our hypothesis, we found that participants became significantly more reliant on feedback visual information with practice ($p<0.001$) but their reliance on feedforward visual information did not change ($p=0.49$). Participants' reliance on visual information increased despite an accompanying change to look significantly farther ahead with practice ($p<0.016$). Together, these results suggest that participants fixated on feedback information less. However,

any change in fixation pattern did not reduce their reliance upon feedback information as individual stepping performance still significantly decreased when feedback information was removed after training. These findings provide important context for how the role of vision in controlling walking changes with practice.

Introduction

People use different types of visual information to control, steer, and maintain stable walking. How people prioritize the different types of visual information informs researchers how they prioritize different motor control strategies. For instance, people who prioritize controlling the current swing limb trajectory to ensure their foot lands in a safe place will fixate their gaze closer to their body (Matthis et al 2018). These feedback fixations (sometimes called “guiding fixations” (Lehtonen et al. 2013, Mennie et al. 2007)), can be operationally defined as fixations less than 1.5 steps ahead. In contrast, people who prioritize locomotor steering and planning efficient future steps will fixate farther ahead. These feedforward fixations (sometimes called look-ahead fixations (Lehtonen et al. 2013, Mennie et al. 2007)), can be operationally defined as fixations greater than 1.5 steps ahead. People typically perform both feedback and feedforward fixations during walking (Patla 2003). Measuring a person’s average fixation distance provides insight into the locomotor control strategies being used in a specific situation.

Healthy adults walking over flat terrain fixate ~2 step lengths ahead (Patla and Vickers 2003). When walking over uneven terrain, healthy adults fixate closer to themselves (Matthis et al. 2018, Thomas et al. 2020, Marigold and Patla 2007), performing more feedback fixations to prevent missteps and limit falls. Similarly, compared to healthy young adults, older adults (Chapman and Hollands 2010, Zietz and Hollands 2009) and people with spinal cord injury or developmental condition disorder (Malik et al. 2017, Warlop et al. 2020) also fixate closer to themselves. These groups may be performing more feedback fixations, taking a more active and visually guided locomotor control strategy to compensate for any gait deficits and ensure accurate foot placement. In contrast, athletic populations typically look farther ahead than non-athletes. Athletes likely rely more on proprioception to guide their current step and may perform more feedforward fixations to inform motor planning (Piras et al. 2010, Aksum et al. 2020). Taken together there may be a correlation between the difficulty of maintaining stable walking and where people direct their gaze.

Fixation distance also changes as people learn a new motor skill. With practice moving a cursor with a novel controller, Sailer and Colleagues (2005) found participants shift from fixating on the cursor (feedback fixations) to fixating on the target (feedforward fixations). Perry and colleagues (2020) found similar results during reaching, with fixation distance increasing as participant performance improved. This shift is often thought to mirror a change in motor control such that people shift from consciously processing and regulating their movement (via feedback control) to more subconscious, feedforward control mechanisms as they improve at a task (Franklin and Wolpert 2011). During walking, conscious control of stepping is associated with an increase in feedback fixations among young adults (Ellmers et al. 2019), older adults (Ellmers 2020) and individuals with Parkinson’s disease (Hardeman 2020). When healthy adults practice and become more skilled at challenging walking tasks, they shift their gaze farther ahead during both obstacle avoidance (Kopiske et al. 2021) and target stepping (Cates and Gordon 2022) tasks. A forward gaze shift during locomotor learning suggests that as people learn to perform a task, their movements become more automated, and the role of vision shifts towards informing feedforward motor control strategies.

One limitation of this prior research is the inherent assumption that the amount of time spent fixating on a location directly correlates with the number of cognitive resources dedicated to that visual location. Stated more directly, if a person is sampling a visual area more, it is interpreted to mean that they are more reliant on that visual information. While this may generally hold true, there are exceptions, and it can't be assumed to be the case in all situations. Described as "Looked But Failed To See" errors (Wolfe et al. 2022), people may trip on a branch despite looking straight at it because they were processing other information rather than the new visual information being collected by their eyes. In the above locomotor learning examples, just because someone is looking farther ahead, it does not necessarily mean they are more reliant on that information. Additionally, people often use peripheral vision to guide foot falls during walking, rather than the central vision measured with eye trackers (Franchak and Adolph 2010). This creates a potential disconnect - an individual may be looking farther ahead on average but are actually using peripheral vision to guide their footfalls. Therefore, to understand the role of vision in controlling walking we must not only quantify where a person looks, but also whether they are using and relying upon the information gathered.

A person's visual reliance has commonly been quantified in standing balance paradigms (Lee, Han, and Hopkins 2022; Hwang et al. 2014) and used to compare the importance of visual information vs proprioceptive or vestibular information. To measure visual reliance, researchers use a knockout paradigm (similar to knockout paradigms in genetic research). Participants complete quiet standing tasks while their visual input is altered (such as via optic flow perturbations (Hwang et al. 2014)). In these studies, any deterioration in performance is interpreted as the reliance on visual information over undisrupted senses, such as proprioception. If a person (such as an older adult) is more affected by the perturbation, they are said to have an over-reliance on vision. One can apply this idea to probe a person's reliance on specific pieces of visual information relative to other visual areas in addition to other sensory inputs. If the person is highly reliant on a specific visual area (for instance being able to see the ground right at heel strike), removing that information should greatly decrease their task performance, even if some visual information (for instance information to guide future steps) is still available. In contrast, if they are not very reliant on a visual area, then removing that information should not significantly change their task performance. Importantly, by using a knockout paradigm, we can decouple where a person is looking from how and whether they are using the visual information being gathered from a particular visual area. To properly understand how locomotor control changes in different populations or situations, it is necessary to quantify both an individual's sampling behavior and their reliance upon the sampled visual information.

Researchers have begun to quantify peoples' reliance on visual information during walking. As expected, healthy adults performing straight walking on flat ground rely very little on processing general visual information, though they do rely on vision during turning (Pham et al. 2011). Older adults rely on vision more than younger adults, with gait becoming more variable (Chapman and Hollands 2006) and more cautious (Marigold and Patla 2008) when vision is temporarily occluded. When examining specific visual areas, occluding feedback fixations has the largest effect on the gait of older adults, leading to larger toe clearances (Kunimune and Okada 2017, Timmis and Buckley 2012) and a more variable foot placement (Reynolds and Day 2005, Matthis 2015) when stepping over obstacles without feedback fixations. Collectively this research suggests that older adults, who often exhibit altered gait patterns, make more feedback fixations, and rely on vision, and in particular feedback visual information, more than young adults.

To understand how the role of vision changes with locomotor learning we must understand the changes to both visual sampling and visual reliance. The present study will therefore examine how individual reliance on processing feedback and feedforward visual information changes with practice of a novel and challenging target stepping task. We hypothesize that, similar to changes in fixation distance, participants will become more reliant on feedforward fixations and less reliant on feedback fixations with practice. We will evaluate any changes in reliance by quantifying changes in the relative stepping performance between limited and full vision conditions. Reliance on feedback visual information would be defined as the difference in performance between the no feedback condition and the full vision condition. With practice, we expect the difference in stepping performance between the no feedback condition and full vision to decrease. In contrast, we expect the difference in stepping performance between the no feedforward condition and full vision to increase with practice. Such results would be in line with changes in visual sampling behavior (namely looking farther ahead with practice (Kopiske et al. 2021, Cates and Gordon 2022)) and support an increased reliance upon feedforward fixations with locomotor learning.

Materials and methods

Participants

20 healthy young adults (14 Women, 24.6 +/- 3.8 years old)) provided written informed consent and participated in the study. Participants were 1.7 +/- 0.1m tall with an average step length of 0.5 +/-0.05 m. Power was confirmed post hoc with a sensitivity analysis (see supplemental information for details). All procedures were approved by the Northwestern University Institutional Review Board. All participants were screened via self-report to ensure they had

normal or corrected to normal vision and did not have any current neuromuscular or musculoskeletal injuries known to affect their balance or gait.

Experimental Setup

Task Environment: Participants were asked to walk on a treadmill and step on a series of projected stepping targets that were moving towards them. All walking occurred on an oversized treadmill (3m x 1.5m, TuffTread, USA). A static board was placed level with the front of the treadmill belt to extend the target viewing space to 4m x 1.5m (board + treadmill belt). Stepping targets (7cm x 15cm) were projected using an overhead projector (Hitachi, Japan) onto the target viewing space.

Motion Capture: We collected 3D kinematic data during walking to quantify foot and head movement. Specifically, we used a 12-camera optical motion capture system with a 100 Hz sampling rate (Qualisys, Gothenburg, Sweden) to collect walking kinematics and quantify real-time stepping behavior. We placed thirteen passive motion capture markers on the participant.

Three non-collinear markers on the head-mounted eye tracker determined the headset viewing plane relative to the lab reference plane. The other 10 markers tracked the 2nd, 3rd, and 5th metatarsals, the lateral malleolus, and the calcaneus of each foot to determine foot locations during gait.

Eye Tracking: Pupil locations were tracked throughout the study to determine fixation locations. To capture fixation location, participants wore a head-mounted eye tracker (Pupil Core eye tracker, Pupil Labs, UK). The headset uses IR reflection to determine the 2D pupil location of

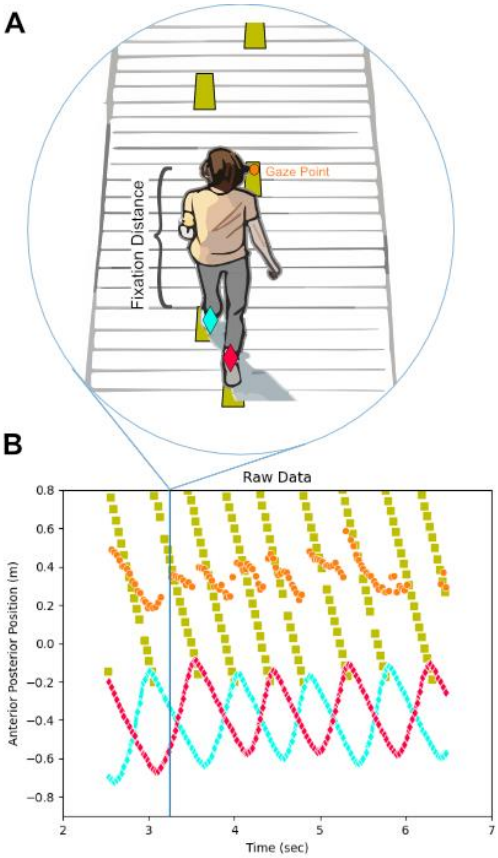

Figure 5-1: A. Diagram of the target stepping task. Stepping targets (in yellow) were projected onto the treadmill, Gaze point (Orange Dot) was calculated based on the eye tracking data. Fixation distance was defined as the distance between the head and the gaze point. Blue and Red diamonds are the calcaneus markers. Shapes and colors match scatterplot in B. B. Scatterplots showing the raw fixation data. Time is on the x axis and Anterior-Posterior distance from the participants head is on the y axis. The yellow squares are the stepping targets. The diamonds are the left (blue) and right (green) heel markers. The orange dots are individual gaze points. The diagram in A is a rough estimation of what is happening at the time point marked by the vertical line in B.

each eye at 200 Hz, which, following a calibration procedure, we transformed into gaze vectors (method for gaze vector calculation described below). Fixation points were defined as the location where the gaze vector intersected with the treadmill surface.

Stepping Task

Full Vision Task: During the full vision stepping task, participants walked on the treadmill while stepping targets were projected onto the treadmill surface (Figure 5-1A). Stepping targets were presented with a set step width (matched to the participant’s preferred step width) and a variable step length (either 80% of preferred step length, preferred step length, or 120% of preferred step length). The targets appeared in a random order of step lengths. Participants were instructed to step on the projected targets as accurately as possible and received auditory feedback (error noise) when the center of the foot (as determined based on the calcaneus and 2nd metatarsal markers) was greater than 0.2 m from the center of the target. The stepping targets were projected such that they moved faster than the treadmill belt speed (two times the speed of the treadmill). Modulating the step error threshold and the speed of the targets are common methods in reaching studies to control task difficulty (Li, Wang, and Cui 2018; Sanchez, Gobel, and Reber 2010) and were selected here after pilot testing to minimize ceiling effects and provide participants with room to improve step accuracy with practice (Cates and Gordon 2022).

Limited Vision Tasks: The limited vision tasks consisted of the same setup and directions as the full vision task. However, the targets were projected such that they were only visible when they were greater than 1.5 steps ahead of the participant (the no feedback condition, Figure 5-2A) or less than 1.5 steps ahead of the participant (the no feedforward condition, Figure 5-2A). The cutoff of 1.5 steps ahead was personalized to each participant based on their preferred step length and was chosen as the dividing line based on previous literature separating visual information related to the current action (feedback) vs visual information for planning future actions (feedforward) (Patla 2003). Participants were still instructed to step on the target (or where the target would be in the no feedback condition) and received the same auditory feedback as the full vision task as if the target was visible. Finally, the targets always moved in a straight line and maintained a constant speed, regardless of whether they were visible to the participant or not.

Experimental Protocol

Participants first completed a series of calibrations. An eye tracker calibration, consisting of the participant fixating on bullseye-style targets projected onto the treadmill, was used to calibrate the participants gaze vectors. A standing calibration determined the flatfoot height of the

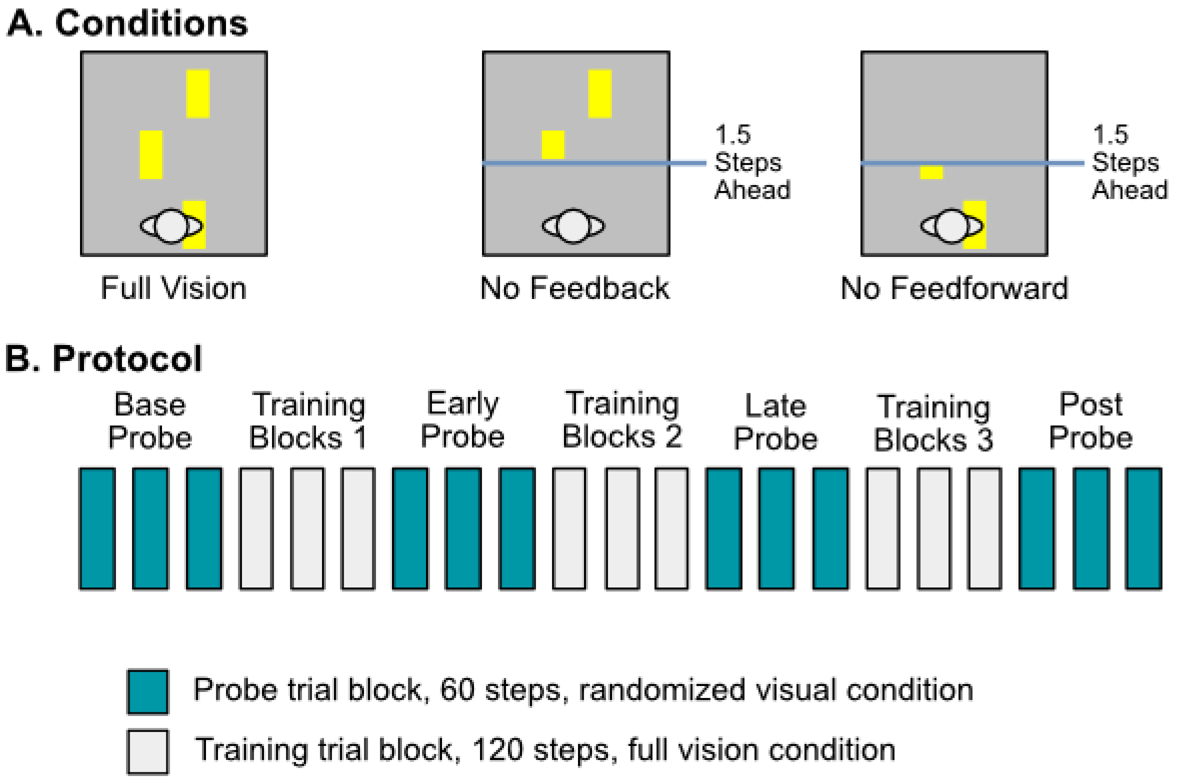

Figure 5-2: A. Aerial view of the treadmill, participant, and targets in the three different conditions. Note the image is not to scale. B. Trial Block Outline

calcaneus markers. We defined real-time heel strike (used to provide auditory feedback) as the time when the calcaneus marker dropped within 5 mm of the participants flatfoot height. Participants also completed a 2-minute walking trial on the treadmill (no targets) to determine their preferred step length and step width at the trial speed (0.9 m/s for all participants and all trials) and define the spacing of the targets during the experimental trials. Following calibration, participants completed a total of 21 trial blocks, alternating in groups of 3 between probe and training trial blocks (Figure 5-2B). During the probe trial blocks, participants completed 60 stepping targets of full vision, no feedback, and no feedforward visual conditions. The order of these three conditions was randomized for each set of 3 probe trial blocks to avoid any order effects. During the training trial blocks, participants completed 120 stepping targets with the full vision task to improve their stepping performance. Participants were given a self-paced break halfway through the experiment (after trial block 10) and were given the option of additional self-paced breaks between the training trial blocks, however most participants did not take any additional breaks. To maintain eye-tracking calibration, participants were not allowed to remove or adjust the eye tracker during any breaks. Additionally, the study ended with participants completing a second eye tracking calibration to check ensure calibration validity throughout the study.

Data Analysis and Processing

Motion Capture Data: Following manual marker correction in Qualisys Tracking Manager software, motion capture data was exported and processed through a custom Python (v3.8) script. Missing marker data (less than 10% of individual marker data) was interpolated using a cubic interpolation through the pandas Python package. After interpolation, the entire trajectory was passed through a 6 Hz low pass filter (Winter et al. 1974).

Eye Tracking: A post hoc calibration and gaze mapping were done using the Pupil Player software (Pupil Labs, UK) before being exported to a custom Python script. The average calibrated accuracy was $1.55^{o} \pm 0.81^{o}$. The x and y position of each pupil and the normalized gaze position on the visual plane were filtered in the following ways: First, the most extreme values (top and bottom 5%) were masked to remove mischaracterizations of the pupils. The data were then interpolated to the nearest point to fill in both the masked data and any missing data from the recording and a median filter with a window size of 10 samples was applied. Due to the smooth pursuit nature of the eye movements, saccades were defined as any time an eye's pupil position changed between aligned frames (100 Hz) more than 0.15 mm (~70 deg/sec) in the x-direction or more than 0.3 mm (~140 deg/sec) in the y-direction. Additionally, any gaze point with lower than 60% confidence (as determined by Pupil Labs) was discarded. To determine the fixation point, we followed the methodology described by Matthis and colleagues (2018) which we have previously reported (Cates and Gordon 2022). Specifically, we created gaze vectors originating at the scene camera of the eye tracker and connecting through the fixation point provided by Pupil Labs on the recorded scene camera image. The scene camera image was arbitrarily defined as residing on a rectangle 1 meter in front of the scene camera. The corners of the rectangle were defined by the intrinsic camera values (103 degrees horizontal and 54 degrees vertical) and the center was located 1 meter in front of the scene camera and normal to the head vector originating at the scene camera. The fixation point on the scene camera image was placed on this rectangle and a gaze vector from the scene camera and through the fixation point was computed. The gaze vector was then projected to intersect with the treadmill plane to determine the fixation point. Representative data is available in Figure 5-1B.

Projected target locations: The location of the projected targets was determined by linearly mapping the projection space into the motion capture system space. To ensure data quality, a unique linear mapping was created for each participant using a projection calibration recording where single points were projected onto the treadmill and markers were placed on top of the projected points.

Data Alignment: Data between the target locations and motion capture were sampled at 100 Hz. They were aligned using the motion capture system frame numbers which were streamed in real-time to the MATLAB program recording and projecting the targets. Gaze data were sampled at 200 Hz and aligned to the motion capture system data by aligning the nearest timestamps.

Outcome Measures

Step Error: Step Error was defined as the Euclidean distance between the center of the foot and the center of the target on the plane of the treadmill at heel strike.

Visual Reliance: Visual Reliance was defined as the increase in step error between a limited vision condition and the full vision condition in the same group of 3 probe trial blocks.

Fixation Distance: Fixation Distance was defined as the Euclidean distance along the treadmill plane between the scene camera on the eye tracker and the gaze fixation point (Figure 1A). When reported, we normalize this distance based on each participant's step length such that distance is reported as the number of steps ahead a participant fixates.

Head Angle: In addition to fixation distance, we recorded participants' head angle. While a participant's head angle is accounted for in fixation distance, head angle has historically been used to approximate fixation distance. By including it here, we both allow for historical comparisons and provide additional validation for fixation distance as head angle data is less processed and more reliable than gaze location. Head angle was therefore defined by the vertical angle between the normal vector to the headset viewing plane and the vertical z-axis.

Toe Off Interval: The toe-off interval was defined as the time (in seconds) between the start of the first fixation onto a target and the toe-off of the foot which will step on the target. A fixation before toe-off is coded as a negative interval while a fixation after toe-off is coded as a positive interval. (See Dominguez et al. 2018 for further description of this metric)

Heel Strike Interval: The heel strike interval is defined as the time (in seconds) between the end of the last fixation on a target and the heel strike of the foot onto the target. A fixation before heel strike is coded as a negative interval while a fixation after heel strike is coded as a positive interval. (See Dominguez-Zamora et al. 2018 for further description of this metric)

Statistical Analysis

For all analyses, the first 6 targets of a trial were removed to allow participants to align their gait pattern with the phase of the stepping targets. The remaining 54 or 114 steps (depending on the trial block) were analyzed for each participant. Significance was set at $p<0.05$ for all analyses unless otherwise specified.

To assess changes in visual sampling, we analyzed how participant step error, fixation distance, and head angle changed across full vision trial blocks. Off treadmill fixations, which accounted for <10% of the data, were considered irrelevant for this analysis. A second-degree mixed effects model with trial number as the fixed effect and subject as a random effect was used to calculate the change across trial blocks for step error, fixation distance, and head angle.

To evaluate if the visual probes did affect gaze behavior, we analyzed how participant fixation distance, toe-off interval, and heel strike interval changed across visual conditions. A mixed linear model with visual condition (no feedback or no feedforward) and probe timing (Baseline, Early, Late, or Post Training) as a fixed effect and subject as a random effect was conducted for fixation distance, toe-off interval, and heel strike interval as outcome measures.

Finally, to determine if visual reliance changed with practice, a mixed effects model tested changes in step error during the probe trials. Visual condition, probe timing, and an interaction effect between visual condition and probe timing were included as fixed effects while the participant was included as a random effect. Should a non-significant result appear, we will test for equivalence using a TOST test with a boundary equal to half of the step error improvement made across full vision condition trials.

Results

Participants

Two participants had poor eye tracking quality and were removed from eye tracking based results (Figures 5-3 and 5-4). However, because the primary result was based on motion capture data alone, both were included in the visual reliance analysis below (Figure 5-5). Data from a representative participant is provided in Figure 5-1B to show how the gaze tracked the targets relative to the participant's feet. We see the participant made individual fixations on each target, though the duration of those fixations is variable.

Step Error decreases while fixation distance increases with practice

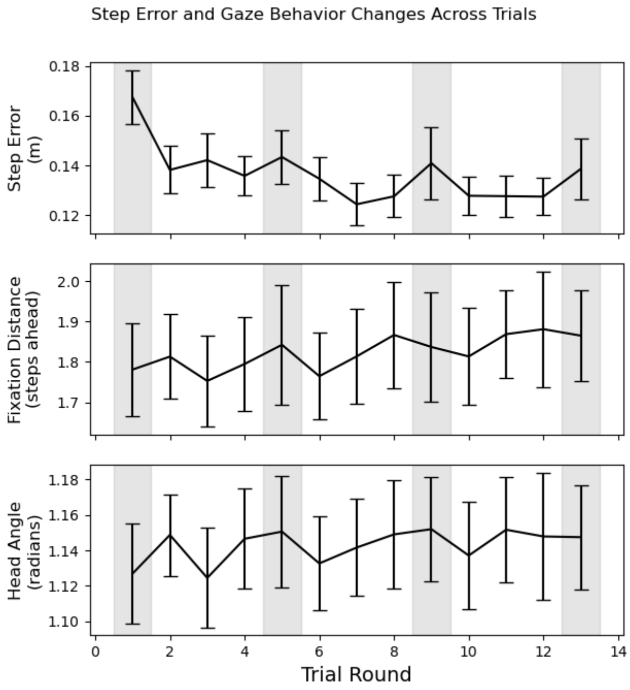

Figure 5-3: Line plots showing mean and SEM for step error (top), Fixation Distance (middle) and Head Angle (bottom) during the full vision trial blocks. Grey vertical bars represent probe blocks where the full vision trial may be in one of 3 trial numbers but were grouped for the graph here. The results show step error decreased while fixation distance increased with practice.

With practice of the full vision task, participants decreased their step error ($p < 0.001$) and looked farther ahead as indicated by significant increases in fixation distance ($p = 0.016$) but not head angle ($p = 0.109$, Figure 5-3). Compared to our previous work (Cates and Gordon 2022), the effect size of the change in fixation distance presented here was smaller than previously found, and there was not a significant change in head angle. To investigate why, a post hoc test was conducted to examine whether the probe visual conditions had lasting effects on the next trial block. A mixed linear model tested whether the fixed effects of trial block, current visual condition, and previous visual condition and random effect of subject affected fixation distance. We found significant main effects for trial block and current visual condition (as expected). We also found a significant fixed effect for the previous trial block on fixation distance. Specifically, fixation distance significantly decreased in the trial blocks following both no feedback ($p = 0.001$) and no feedforward ($p < 0.001$) trial blocks.

Limiting visual targets affected gaze behavior

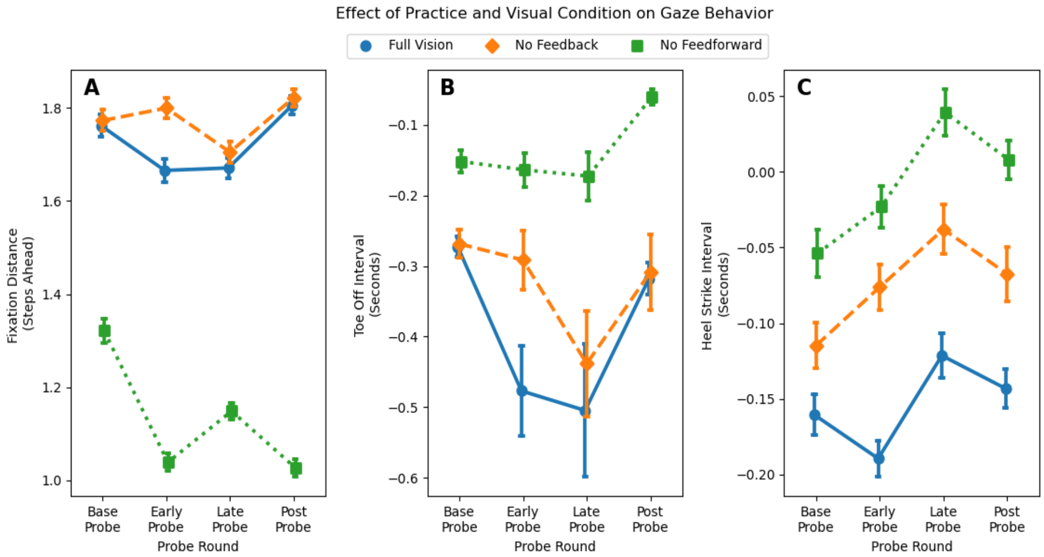

Figure 5-4: Changes in Gaze Behavior during the visual probe conditions with practice. Line plots show the mean and standard error for the fixation distance (A), Toe off interval (B) and Heel Strike interval (C) across probe rounds. The negative values in B and C suggest that Toe off (B) and Heel Strike (C) occurred after the initial fixation started (B) or last fixation ended (B).

To confirm that our intervention had the intended effect, we compared whether removing stepping targets changed gaze behavior. As expected, we found the no feedforward condition led to significantly closer fixations than the no feedback ($p < 0.001$) and full vision ($p<0.001$) conditions (Figure 5-4a). The result confirms that participants directed their gaze closer to themselves in the no feedforward condition as that was where the targets were visible. The no feedback condition, however, did not significantly change participant fixation location ($p=0.45$), likely due to the targets still being visible in the default, full vision location. The no feedforward condition also led to a significantly shorter toe-off interval (the time between the first fixation and start of the movement) compared to the no feedback and full vision conditions ($p <0.001$, Figure 5-4b). As expected, participants transferred their gaze to the next step later, likely due to information about the next target not being available until later in the gait cycle. The no feedback condition, again, did not significantly change the toe off interval compared to the full vision condition (p=0.78). In contrast, we found both the no feedback (p = 0.011) and no feedforward (p < 0.001) conditions exhibited significantly more positive heel strike intervals (the time between the end of the last fixation on the target and the end of the movement) than the full vision condition (Figure 5-4c). While expected in the no feedforward condition (due to where the targets were visible), this suggests that participants looked their foot to where they thought the target should be in the no feedback condition, even though they could not see the target.

Reliance on feedback visual information increases with practice

When testing for visual reliance, we find a significant interaction effect between probe timing and step error. Pairwise testing revealed a significant difference between visual conditions, with participants performing worse during the no feedback (corrected p<0.001) and no feedforward (corrected p=0.038) visual conditions, compared to full vision (Figure 5-5A). The pairwise testing also revealed a significant change in the reliance on feedback (p < 0.001) but not in the reliance on feedforward (p = 0.49) visual information with practice. As seen in Figure 5-5B and

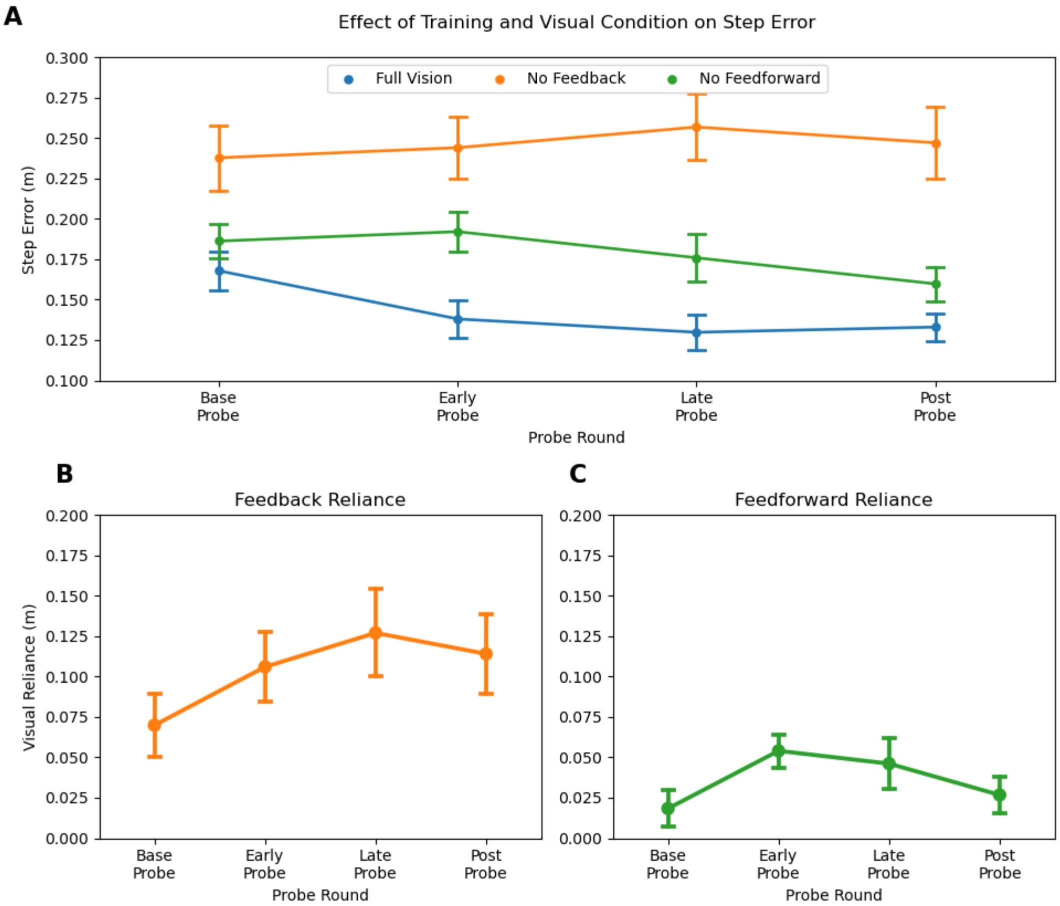

Figure 5-5: A. Mean and SEM of step error during the four probe periods, split by visual condition of the probe. B and C show mean and standard error of the computed feedback (B) and feedforward (C) visual reliance during the 4 probe rounds. Feedback Visual Reliance was calculated as the difference between the No Feedback (Blue) and Full Vision (Green) conditions shown on Figure A. Similarly, Feedforward Visual Reliance was calculated as the difference between the No Feedforward (Orange) and Full Vision (Green) conditions shown in Figure A.

C, participant reliance on feedback information increases with practice, while reliance on feedforward information appears unchanged. An equivalence test, however, failed to reject the null (p=0.28) suggesting that we cannot reject the possibility of a significant change in feedforward reliance.

Similar to stepping performance, participant gaze metrics changed with training. A mixed linear model found significant interaction effects between visual condition and trial for fixation distance (p<0.001), toe off interval (p<0.001), and heel strike interval (p<0.001). Specifically, in the no feedforward condition participants fixated closer to themselves over time (vs fixating farther ahead with practice during full vision and no feedback conditions, Figure 5-4A). They also changed their toe off interval (Figure 5-4B) and heel strike interval (Figure 5-4C) significantly less in the no feedforward condition than the full vision and no feedback conditions, though they were directionally the same.

Discussion

We aimed to measure how reliance on feedback and feedforward visual information changes with locomotor learning. We hypothesized that participants would increase their reliance on feedforward information and reduce their reliance on feedback information. However, our results do not support this hypothesis. As expected, participants improved at the task and shifted their fixation distance farther ahead with practice (Figure 5-3). However, they also increased their reliance on feedback visual information with practice (Figure 5-5). The results suggest that while visual sampling behavior may shift towards greater sampling of feedforward visual information, people also become increasingly reliant on the feedback visual information they do collect.

With practice, participants improved at the task, significantly decreasing their step error. This decrease in step error was accompanied by an increase in fixation distance, replicating our previous findings (Cates and Gordon 2022). However, the increase in fixation distance is smaller than our previous study, likely because of the intermittent probe trials. Previous research suggests gaze behavior during walking can be impacted by individual confidence (Thomas et al. 2020) or fall anxiety (Ellmers et al. 2019). Our post hoc results are in line with this idea. Participants struggled during the limited vision conditions, exhibiting more step errors, and thus hearing the corresponding auditory error noise more frequently. Participants therefore knew they were not very successful at the task, which may have lowered confidence going into the next trial block (regardless of the next block's visual condition) and increased the propensity for conscious movement processing (van Ginneken et al. 2018). The reduced confidence and increased conscious movement processing likely caused participants to fixate closer to themselves (Ellmers et al. 2020) and reduced the overall change in fixation distance across the study. Despite this limitation, the results do support our previous research suggesting that practicing a continuous target stepping task leads to an increase in fixation distance.

We expected that increasing fixation distance would be associated with an increased reliance on feedforward visual information. However, that is not what we found. Counter to our hypothesis, participants became more reliant on feedback visual information with practice. Taken together, our results suggest that while participants may be looking farther ahead, they are still reliant on the feedback visual information they receive.

One possible explanation for this disconnect may be that participants became more visually flexible, meaning they improved their ability to use whatever visual information was available to successfully perform the task. With practice of typing tasks (Ariani et al. 2021, Bashford et al. 2022), participants were able to use visual information farther ahead in time to improve their performance. However, when future information was removed in these studies, participant performance did not significantly drop. Instead, participants were visually flexible, able to use the available information to complete the task. Similarly, in our study, participants were able to rapidly shift where and when they were directing their gaze based on the visual condition. They also improved their stepping performance in the full vision and no feedforward conditions, suggesting an artificially shorter planning horizon did not prevent motor learning. The importance of confirming accurate foot placement in the target stepping task may have led participants to continue to rely on feedback visual information. Therefore, the learning, may have resulted in improved efficiency (as evidenced by the increasing fixation distance resulting in less time spent on feedback fixations), but did not change visual reliance (as evidenced by the increasing reliance on feedback visual information).

Another explanation may be that participants became more adept at using peripheral vision to guide foot placement. Research suggests that people have increased peripheral awareness during walking (Cao and Handel 2019) compared to when they are stationary. Additionally, when navigating obstacles in the real world, adults use central vision to fixate on the obstacle less than children and infants (Franchak and Adolph 2010). This transition is supported more generally by Perry and colleagues (2020) who found people used peripheral vision more effectively and frequently as they practiced and improved at a reaching task. Our participants may have been able to increasingly rely on peripheral vision to guide their stepping, allowing them to keep their central fixation (which was quantified in this study) farther ahead. However, when the targets were removed, feedback visual information was occluded from both peripheral and central vision alike. In this case, our participants’ use of peripheral vision was unable to help them perform the task. General visual reliance was likely exacerbated by the visually dependent nature of the task, with the targets only being a visual projection with no way to provide tactile feedback. Future studies should look to quantify the utilization of peripheral vision to determine if locomotor learning increases its use.

While the increased reliance on feedback visual information is surprising, the continued reliance on feedback visual information is in line with visuo-locomotor training literature. A few studies (Gunn et al. 2019, Young and Hollands 2010) have attempted to rehabilitate locomotor performance by emphasizing where participants should look. Specifically, these studies emphasized feedback visual information, under the assumption that vision would make up for other deficits such as proprioception deficits. These studies found participant performance improved with these visual guidance interventions, suggesting that emphasizing feedback visual information is still important for improving locomotor performance. When combined with our present results, we would recommend training that emphasizes the general use of visual information without dictating where individuals should look. People likely need to collect the entirety of the visual field to best train at a task, though specific interventions modulating what information is available during training (compared to the constant full vision training employed here) is likely necessary to test this hypothesis.

The findings of the present study may have been limited by the task design. First, because the stepping targets were moving faster than the treadmill, the task may be more akin to stepping on a bug than walking in rocky terrain. The changes to both the step error threshold and the speed of the targets were to ensure participants demonstrated a learning effect as shown in our previous work (Cates and Gordon 2022). Future work should look for other methods to create a similar learning task that transfers more easily to a real-world environment, possibly by modulating the speed of the treadmill belt. Second, by breaking the probe trials into separate trial blocks, it is possible that participants approached the probe trials as a different task altogether. Different strategies across participants may also account for the large inter-subject variability in performance during the no feedback condition. Third, the no feedback condition was especially unforgiving in terms of step error. Without visual feedback, participants would occasionally make repeated errors as they were unable to correct the previous step, leading to them being increasingly off with each successive step. These trends were also not evenly distributed across participants, with some participants consistently making repeated errors while others were able to adapt. To assess if the results were driven by these repeated errors, we conducted a post-hoc test looking at visual reliance only including the first inaccurate step (and ignoring subsequent consecutive errors). This method did not change the direction of our results, with participants still increasing their reliance on feedback visual information, though this result was no longer a significant change (p=0.44). Future studies should look to embed the limited vision conditions into a larger full vision trial. This would allow for quick probes without providing participants with the chance to change locomotor controls strategies and may therefore reduce the inter-subject variability. Additionally, because the probes are short, participants would be able to correct their foot placement quickly once full vision is restored, limiting repeated errors.

Overall, the present results suggest that gaze behavior is flexible, changing both with increasing motor skill and in response to limited visual conditions. However, visual reliance does not change in the same way as visual sampling. Participants became increasingly reliant on feedback visual information while practicing the target stepping task, despite shifting their central gaze fixation farther ahead. These opposing results may be explained by increased efficiency of visual processing or through the increased use of peripheral vision. Future research should continue to quantify both visual sampling strategies and visual reliance at different stages of locomotor learning. Such quantification may lead to a better understanding of how the role of vision to control walking changes with training.

Acknowledgements

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Chapter 6: Gaze behavior during walking is unaffected after recovery from a concussion

Abstract

Concussions are one of the most common neurological injuries in the United States, causing a wide range of symptoms that can persist well past the normal recovery period. Impairments in gait are one such persistent effect commonly reported, often lasting weeks or months after the cognitive symptoms have recovered, though the cause of these persistent deficits is unknown. Here, we examine whether changes in gaze behavior, specifically where people look and how much they rely on vision, may be related to these gait deficits. Twelve individuals who were recently (<2 weeks) medically cleared from a concussion and 12 matched controls were recruited to complete two target-stepping tasks. While the results suggest that individuals post-concussion exhibit persistent deficits in oculomotor control and standing balance, participants did not exhibit significant gait deficits, nor changes in gaze behavior. While task design may have limited the present study, the results suggest that visuomotor deficits are not related to persistent gait deficits. Future research should look to confirm the results as well as explore other explanations, such as proprioceptive deficits.

Introduction

Mild traumatic brain injury, commonly referred to as a concussion, is one of the most common neurological injuries in the United States. An estimated 4 million Americans are diagnosed with a concussion every year (Harmon et al. 2013), affecting a diverse population including young adult athletes (King et al. 2014), military service members (Hoge et al. 2008; Nelson and Esty

2015), and older adults (Korhonen et al. 2013). The prevalence of concussions is concerning, with the concussion rate in older adults tripling in recent years (Korhonen et al. 2013) and 20% of high school athletes self-reporting that they have experienced at least one concussion (DePadilla et al. 2018). Additionally, suffering one concussion triples the chances of a second concussion (Cantu 2003; Guskiewicz et al. 2000) and can cause a wide range of secondary comorbidities. To effectively counteract the long-term consequences of a concussion, we must better understand the functional deficits and associated recovery. While short-term cognitive deficits following a concussion are well documented (Hallock et al. 2023), concussions also produce a range of other impairments, such as oculomotor (Parker et al. 2007), vestibular (Ellis et al. 2015), and gait (Wood et al. 2019) deficits which require further study.

Gait and balance deficits are of particular interest, as they limit daily living activities and can persist for weeks, months, or even years after the concussion has clinically resolved (Wood et al. 2019; De Beaumont et al. 2009). These altered gait patterns include a slower, more cautious gait (Buckley et al. 2016), shortened gait termination (Buckley et al. 2013), and suboptimal turning mechanics (Fino, Nussbaum, and Brolinson 2016). The persistence of these deficits likely contributes to other comorbidities common after a concussion (Howell et al. 2018). For instance, athletes with a history of concussions who have been medically cleared to return to play are over 3 times more likely to suffer a lower extremity, musculoskeletal injury than their non-concussed counterparts (Herman et al. 2017; Harada et al. 2019; Brooks et al. 2016; Nordström, Nordström, and Ekstrand 2014). Identifying potential mechanisms is necessary to prevent these secondary injuries. Eagle and colleagues (2020) proposed that deficits in visual perception and visuomotor processing may be a root cause for persistent motor control deficits following a concussion. While there are several potential aspects of visuomotor processing that could be examined, the present study focuses on: 1) altered visual fixation locations; 2) altered visual reliance; and 3) altered visuo-locomotor learning.

Visual Fixation Locations

One possible cause of persistent locomotor deficits may be that following medical clearance from a concussion, people are not sampling the necessary visual information to guide walking safely and efficiently. Following a concussion, oculomotor (eye movement) deficits are common (Murray et al. 2019; Ellis et al. 2015). Impairments in how the eyes can move may constrain what visual information a person collects by limiting where they are able to look. Limitations in where people can look will limit what visual information they are able to collect, possibly depriving people of information necessary for motor control. Experimentally, limiting visual information among individuals with a concussion negatively affects standing balance (Ellis et al. 2015), although this phenomenon has not been investigated during gait. When we examine other populations with gait impairments, even if there are no oculomotor deficits present, we find altered visual fixation locations. For instance, older adults tend to focus their gaze closer to themselves while maintaining a slower, more cautious gait and exhibiting poor standing and walking balance (Graham John Chapman and Hollands 2010; Young and Hollands 2012; Zietz and Hollands 2009; Jeka et al. 2006). People with coordination disorders similarly emphasize fixating on the current step rather than planning for future actions (Warlop et al. 2020) while people post-stroke exhibit altered visuomotor coordination during turning (Lamontagne et al. 2010). Individuals post-concussion exhibit the same changes in their gait pattern as other gait-deficient populations. Therefore, the present study will examine whether visual sampling behavior is altered following medical clearance from a concussion.

Visual Processing and Reliance

Even if people who have recovered from a concussion are able to look at the necessary visual areas and collect the associated visual information, they may still struggle with visual processing. Many reported gait deficits following a concussion are only apparent during complex walking, such as when walking in cognitively demanding environments or under additional cognitive load (Fino et al. 2018; Lee, Sullivan, and Schneiders 2013). For instance, dual-task interference, where people must concurrently perform a cognitive task while walking, often leads to the expression of a variety of gait deficits among individuals post-concussion when compared to people who have never had a concussion (Fino et al. 2018). Similarly, when stepping over an obstacle (to create a complex environment), people with a concussion walk slower and display greater landing displacement than matched controls (Catena, van Donkelaar, and Chou 2007). With complex environments (e.g. uneven ground) and additional cognitive load (e.g. as talking with someone while walking) common in daily life, we are always executing complex walking. In people post-concussion, visual processing may therefore be constantly marginalized for other cognitive processes. Marginalizing visual processing may have an even larger effect on gait among individuals post-concussion due to an increased visual reliance. Other populations, such as older adults (Timmis and Buckley 2012) and people with neurological disorders (Selgrade et al. 2020; Lamontagne, Paquette, and Fung 2007) display an increased reliance on visual information during walking. If individuals post-concussion combine this same increased reliance on visual information with decreasing cognitive resources dedicated to processing visual information, then they are likely to struggle to maintain a safe and efficient gait pattern. Thus, it is possible that people post-concussion collect the necessary visual information to perform walking tasks in complex environments, but do not process the information correctly, leading to changes in gait.

Visuo-Locomotor Learning

Finally, people post-concussion may have motor learning impairments, limiting their ability to adapt to changing environmental demands during walking. Preliminary evidence suggests motor learning deficits are present during the acute stages of a concussion (De Beaumont et al. 2009; Bourassa et al. 2021) and that these deficits become more pronounced with repeated concussions (Cantarero et al. 2020). Stable walking demands ongoing adaptation of the natural gait pattern to meet changing tasks and environmental demands (Hak et al. 2013). While the reported motor learning deficits are in reaching tasks, should they apply to locomotor learning, they could lead to a more cautious locomotor strategy. Therefore, people post-concussion may recover the ability to visually control walking similar to before the concussion (including normal visual sampling and reliance) but are unable to adapt their gait patterns in response to ever-changing environmental demands.

The Present Study

The present study, therefore, aims to investigate whether altered visual fixation locations, visual reliance, and/or visuo-locomotor learning could be a potential mechanism behind the persistent gait deficits in people post-concussion. Specifically, participants performed a precision stepping task while their gaze was monitored (Cates and Gordon 2022). Visual fixation distance was monitored throughout to assess if people post-concussion looked at the same visual areas. Visual reliance was assessed for both feedback and feedforward visual fixations, similar to previous work in healthy young adults (Chapter 5) and older adults (G. J. Chapman and Hollands 2006;

Kunimune and Okada 2017; Marigold and Patla 2008). Finally, their visuo-locomotor learning ability was quantified as the rate of change in step accuracy and fixation distance with practice (Cates and Gordon 2022). We hypothesized that individuals who recently recovered from a concussion would fixate closer to themselves and display a greater reliance on visual information to perform the task. We also expected individuals to have reduced visuo-locomotor learning following a concussion, indicative of deficits in their ability to adapt their gait pattern to meet environmental demands.

Methods

Participants

12 individuals less than 2 weeks post medical clearance from their concussion and 12 matched controls were recruited for the present study (table 1). Medical clearance was defined as all symptoms returning to baseline, as determined by a clinician in the Sports Medicine Department of the Northwestern Medicine Student Health Services. Control participants were matched on age (+/- 2 years), sex, and athletic level (not an athlete, intramural athlete, or club sport athlete). All participants completed a written informed consent as approved by the Northwestern University Institutional Review Board.

Table 6-1: Demographic information

	Individuals Post Concussion	Matched Controls
N	12	12
Age (mean)	21.9 +/- 4	22.3 +/-3.9
sex (No. Women)	10	10
Height (mean cm)	167 +/- 8	163 +/- 6
Step length (mean cm)	50 +/- 4	48 +/- 2
Days to medical clearance (mean)	34.5	N/A

Experimental Setup

Stepping Task: Participants were asked to walk on a treadmill and step on a series of projected targets that were moving towards them. All walking occurred on an oversized treadmill (3m x 1.5m, TuffTread, USA). A static board was placed level with the front of the treadmill belt to extend the target viewing space to 4m x 1.5m (board + treadmill belt). Stepping targets (7cm x 15 cm) were projected on the treadmill belt surface using an overhead projector (Hitachi, Japan).

Motion Capture: We collected 3D kinematic data during walking to quantify foot and head movement. Specifically, we used a 12-camera optical motion capture system operating at 100 Hz (Qualisys, Gothenburg, Sweden) to collect walking kinematics and quantify real-time stepping behavior. We placed thirteen passive motion capture markers on the participant. Three non-collinear markers on the head-mounted eye tracker determined the headset viewing plane relative to the lab reference plane. The other 10 markers tracked the 2nd, 3rd, and 5th metatarsals, the lateral malleolus, and the calcaneus of each foot to determine foot locations during gait.

Eye Tracking: Pupil locations were tracked throughout the study to determine fixation locations. To capture fixation location, participants wore a head-mounted eye tracker (Pupil Core eye tracker, Pupil Labs, UK). The headset uses IR reflection to determine the 2D pupil location of each eye at 200 Hz, which, following a calibration procedure, we transformed into gaze vectors. 2 different calibration processes were used, one for oculomotor testing with participants fixating on a laptop screen (see oculomotor testing below for details) and another for the visuo-locomotor testing where participants were fixating on the treadmill surface (see eye tracking data in Data Analysis and Processing for details).

Baseline Testing

To ensure that individuals post-concussion had recovered according to the clinical definitions and to test for any underlying deficits which may impact performance, we conducted three baseline tests to check oculomotor, balance, and step reaction time, respectively.

Oculomotor Testing

To assess baseline oculomotor ability and check for any persistent oculomotor deficits following recovery, we performed a computerized oculomotor test. The test was based on the King Devick Test (Galetta et al. 2011, Rizzo et al. 2016) which, when combined with eye tracking, has been shown to identify oculomotor deficits in individuals with a concussion. In our custom version, participants read a series of numbers presented on a 13.5" laptop screen (resolution 3000x2000)

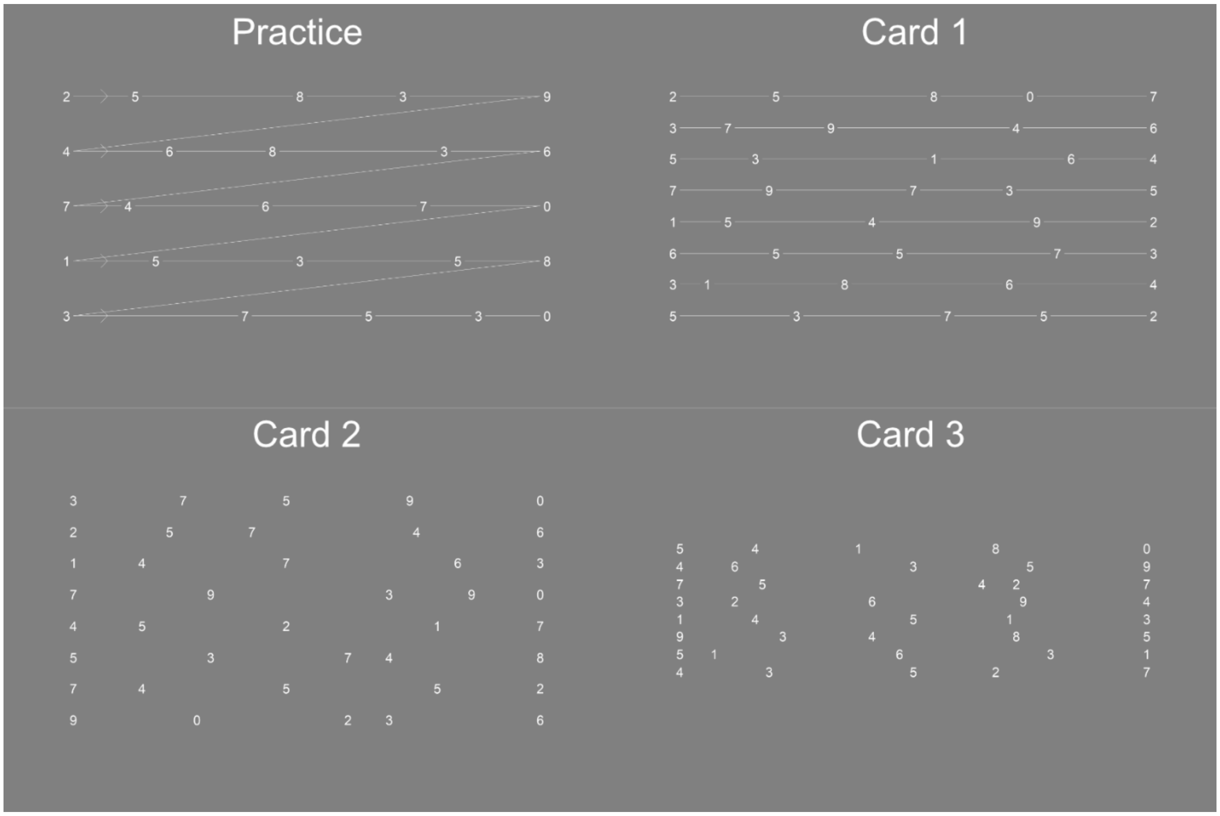

Figure 6-1: Screenshots of the 4 test cards used in the oculomotor testing. The task became increasingly difficult through the removal of guidelines and reduction of spacing. Labels for each card have been added and were not displayed to the participant.

as quickly and accurately as they could. Participants sat directly in front of the laptop ~0.6 m from the screen at all times. All participants read the same cards displayed on the screen (see Figure 6-1). Participants were asked to read each card out loud “as quickly and accurately as possible, with accuracy more important than speed”. Participants progressed through 4 cards in order, a practice, and 3 trial cards, then repeated the set of 4 cards (for 8 total cards shown). The cards were displayed on the laptop screen using a custom Python script. Participant reaction time and verbal reading of the cards were recorded using the same Python script. A head-mounted eye tracker was used to record eye movements during the task.

Total performance time, number of errors, and number of fixations made during each trial card were used as the outcome measures. To determine the number of errors made during each trial of the oculomotor testing, a custom Python (v3.8) script was used to process the auditory recording. The speech recognition Python package (Zhang 2017) was used to generate a transcript of each trial. The transcript was then cleaned to remove any extra pauses and letters and to convert all numbers to numerals (e.g., convert “one” to “1”). The transcript was then compared to the ideal transcript and checked for errors performed by the participant including missing numbers, extra numbers, and repeated numbers. To determine the number of fixations, fixation data was exported using the Pupil Player software (v3.5.1, Pupil Labs, UK) based on the calibration done on the laptop and the fixation detector plugin. The average calibrated accuracy was 1.68° ± 0.79°. Fixations were determined with a maximum dispersion was 1.5° and a duration between 80 and 220 ms. Three linear mixed models (using the statsmodels package and a custom Python script) were performed for total performance time, the number of fixations, and the number of errors, respectively. Each model included the experimental group, the trial card, and the interaction between the two as fixed effects and the subject as a random effect.

Modified Clinical Test of Sensory Integration and Balance

The modified clinical test of sensory integration and balance (m-CTSIB) was used to assess baseline balance ability (Moran et al. 2020). Participants completed a total of eight standing trials on top of a force plate (AMTI, Watertown, MA), two trials with eyes open on flat ground, two trials with eyes closed on flat ground, two trials with eyes open while standing on destabilizing foam, and two trials with eyes closed while standing on destabilizing foam. Participants were asked to stand still for 30 seconds with their feet together, their ankles together, and their arms at their sides.

The center of pressure was sampled at 1000 Hz using the force plate and fed into a custom Python (v3.8) script. The center of pressure was mean aligned (such that the new origin was at the mean x and y location of the raw recording). The recording was then clipped to include 20 seconds of recording (removing the initial stabilization period) during which the participant was tasked with maintaining a still stance. The stabilogram python package (Quijoux et al. 2021) was then used to compute the area of the 95% confidence ellipse of sway for each trial of each subject. A linear mixed model was performed with visual condition (eyes open or closed), surface (standing on flat ground or foam), experimental group, and all their interactions as fixed effects with the subject as a random effect. A significant effect of the experimental group would suggest a difference between individuals post-concussion and matched controls, while the interaction effects may speak to specific sensory deficits. Significant effects of visual condition and surface are expected as the task is designed manipulate these factors to increase the difficulty of standing still. Should an interaction effect be found, a pairwise Tukey test will be used to compare the experimental groups across the four conditions.

Step Reaction Time

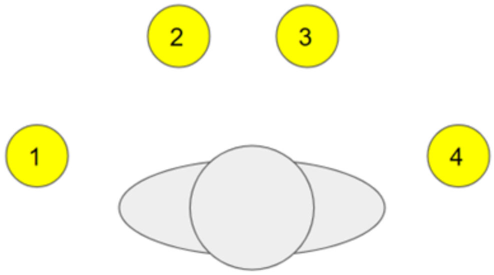

Figure 6-2: Top-down view of the step reaction task. Targets would appear one at a time in one of the 4 locations. Participants had to step with their left foot for targets 1 and 2, and their right foot for targets 3 and 4. Not to scale.

To measure step reaction time, participants stood on flat ground with feet shoulder width apart (Figure 6-2). Stationary projected targets (Circles, 10 cm radius) would appear on the ground in one of four locations (side left, forward left, forward right, and side right) and participants were asked to step on the target as quickly as possible with the nearest foot before returning to the home position. Participants completed a total of 20 step trials. Because this test was added partway through data collection, only 5 matched pairs completed the step reaction time test (5 individuals post-concussion and their 5 matched controls).

The movement start time was used as the primary outcome measure, defined as the time between when a stepping target appeared and when the person began their movement. This was calculated algorithmically using a custom Python script and motion capture data based on the start of the peak associated with the height of the calcaneus marker during the movement. A participant’s average reaction time was computed across all trials. A linear mixed model was then performed with the experimental group as the fixed effect and the subject as the random effect.

Target Stepping Tasks

To assess participant gaze behavior during walking, participants completed multiple versions of a target stepping task. The standard version is described first, followed by the modifications and their purposes.

Standard Stepping Task: Testing Visual Fixation Location

The standard stepping task consisted of participants walking on the treadmill (0.9m/s) while stepping targets were projected onto the treadmill surface. Stepping targets were presented with a set step width (matched to the participant's preferred step width) and a variable step length (either 80% of preferred step length, preferred step length, or 120% of preferred step length). Participants were instructed to step on the projected targets as accurately as possible and received auditory feedback (an error noise) when the center of the foot was greater than 0.2 m from the center of the target at heel strike. The speed, visibility, and order of the targets were manipulated as described below depending on the specific task.

Across both modified versions, fixation distance was monitored and compared to assess if individuals post-concussion fixate at the same locations as matched controls. Fixation distance was defined as the Euclidean distance along the treadmill plane between the scene camera on the eye tracker and the gaze fixation point. This distance was normalized based on each participant's step length such that distance is reported as the number of steps ahead a participant fixates. Average fixation distance was computed across all the embedded and sequenced trials, respectively. Two linear mixed models (one for embedded trials and one for sequenced trials) were used to assess if fixation distance (the outcome measure) significantly differed based on the experimental group (fixed effect) or subject (random effect).

Embedded Stepping Task: Testing Visual Reliance

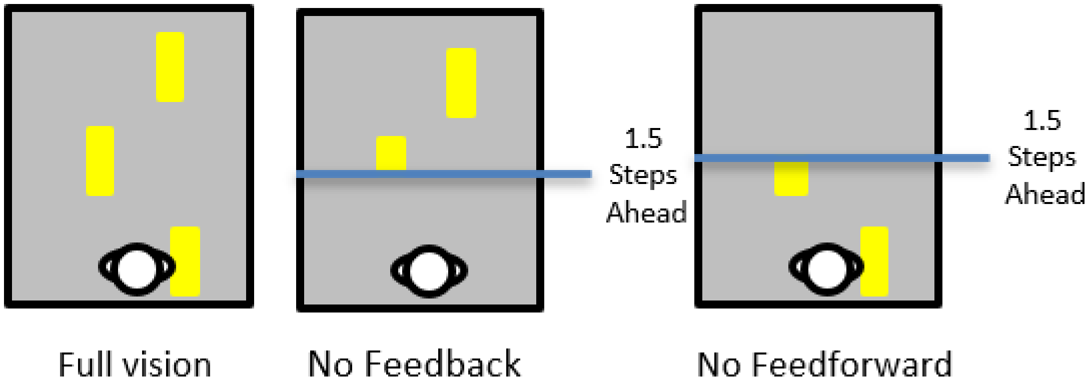

Figure 6-3: A top-down visualizations showing a person walking on the treadmill during each of the 3 visual conditions. Note depiction is not to scale.

During the embedded stepping task, targets were projected in a random order of step lengths with a target speed that matched the speed of the treadmill. The visibility of the targets was manipulated throughout each trial block. In each trial block of 120 steps, participants completed four periods of limited vision, two with no feedback and two with no feedforward visual information (Figure 6-3). The limited vision periods lasted for six consecutive steps and were interspersed with 15-20 full vision targets in between (jittered to limit anticipatory effects). The no-feedback condition hid targets that were less than 1.5 steps ahead of the participant, while the no-feedforward condition hid targets that were greater than 1.5 steps ahead of the participant (Figure 6.3). The cutoff of 1.5 steps ahead was personalized to each participant based on their preferred step length. 1.5 steps were chosen as the dividing line based on previous literature separating visual information related to the current action (feedback) vs visual information for planning future actions (feedforward) (Patla 2003). Participants were still instructed to step on the target (or where the target would be in the no-feedback condition) and received the same auditory feedback as during the standard stepping task. Finally, the targets always moved in a straight line and maintained a constant speed, regardless of whether they were visible to the participant or not.

Participant step error, defined as the Euclidean distance between the center of the foot and the center of the target on the plane of the treadmill at heel strike, was monitored. Visual reliance was then calculated by subtracting step error during the limited vision conditions from the full vision condition during each embedded trial block. A large difference between the visual conditions connotes a large reliance on the respective visual information. Two linear mixed models were used to assess if feedback or feedforward visual reliance (the outcome measures, respectively) significantly differed based on the experimental group (the fixed effect) or subject (the random effect).

Sequenced Stepping Task: Testing Visuo-Locomotor Learning

During the sequenced stepping task, the target projections were always visible. To help test locomotor learning, the targets were projected in a 6-step repeating pattern of step lengths, specifically 100%-80%-120%-80%-100%-120%. With practice of a similar 6-step pattern, healthy adults will improve their step accuracy and increase their fixation distance (Cates and Gordon 2022; Choi, Bouyer, and Nielsen 2015). The targets were also projected at twice the speed of the treadmill in the sequenced stepping task to limit ceiling effects (Cates and Gordon 2022). Participants received the same instructions and feedback as in the standard stepping task and were made aware that the targets would be faster than the treadmill but were unaware of the repeating pattern.

Both the change in step accuracy and fixation distance over time were considered as evidence of visuo-locomotor learning, with the rate of these changes compared between experimental groups.

Two mixed linear models were performed, one with step error and one with fixation distance as the outcome measures. Each model had the experimental group, trial block number, and the interaction between the experimental group and trial block number as fixed effects, and the subject as the random effect. A significant interaction effect would suggest altered visuo-locomotor learning. A significant effect of the trial block is expected based on previously reported effects on how practice affects step error and fixation distance (Cates and Gordon 2022) while a significant effect of the experimental group would suggest either persistent gait deficits (for step error) and support the fixation distance results (for fixation distance).

Experimental Protocol

Following informed consent and demographic information collection, participants completed the m-CTSIB to assess balance. The eye tracker was then set up and calibrated to the laptop screen for oculomotor testing. This calibration was a standard 5-point calibration provided by the Pupil Capture software (v3.5.1) with targets appearing in the center and each of the 4 corners of the screen. Participants then completed the oculomotor testing before moving to the treadmill. A second eye-tracking calibration was then performed with participants fixating on a series of 40 bullseye-style targets projected onto the treadmill at various locations. An additional standing trial was then recorded with motion capture to determine the flatfoot height of the calcaneus markers. We defined real-time heel strike (used to provide auditory feedback) as the moment when the calcaneus marker dropped within 5mm of the participant's flatfoot height. Participants also completed a 2-minute walking trial on the treadmill (no targets) to determine their preferred step length and step width at the trial speed (0.9 m/s for all participants and all trials) and define the spacing of the targets during the experimental trials. Participants then completed the step reaction time task with normalized step lengths.

Following the completion of the baseline and calibration procedures, participants completed 10 trial blocks of the embedded stepping task, received a self-paced break of at least 5 minutes, and then completed 10 trial blocks of the sequenced stepping task. Each trial block consisted of a total of 120 stepping targets. Participants were also given the option of additional self-paced breaks between any trial blocks; however, most participants did not take any additional breaks. To maintain eye tracking calibration, participants were not allowed to remove or adjust the eye tracker during any of the breaks, additionally, single target calibration checks were performed every 5 trial blocks and a complete second eye tracking calibration was performed after the entire task to help control for any drift.

Data Analysis and Processing

Motion Capture Data: Following manual marker correction in Qualisys Track Manager software, motion capture data was exported and processed through a custom Python (v3.8) script. Missing marker data (less than 10% of individual marker data) was interpolated using a cubic interpolation through the pandas Python package. After interpolation, the entire trajectory was passed through a 6 Hz low pass filter (Winter, Sidwall, and Hobson 1974).

Eye Tracking Data: For the visuo-locomotor testing, post hoc calibration and gaze mapping were done using the Pupil Player software (v3.5.1, Pupil Labs, UK) before being exported to a custom Python script. The average calibrated accuracy was 1.75° ± 0.9°. The x and y position of each pupil and the normalized gaze position on the visual plane were filtered in the following ways. First, the most extreme values (top and bottom 5%) were masked to remove mischaracterizations of the pupils. The data were then interpolated to the nearest point to fill in both the masked data and any missing data from the recording. A median filter with a window size of 10 samples was then applied. Due to the smooth pursuit nature of the eye movements, saccades were defined as any time an eye's pupil position changed between aligned frames (100 Hz) more than 0.15 mm (~70 deg/sec) in the x-direction, or more than 0.3 mm (~140 deg/sec) in the y-direction. Additionally, any gaze point with less than 60% confidence (as determined by the Pupil Player software) was discarded. To determine the fixation point, we followed the methodology described by Matthis and colleagues (Matthis, Yates, and Hayhoe 2018) which we have previously reported (Cates and Gordon 2022). Representative data is available in Figure 6-4

Projected target locations: The location of the projected stepping targets was determined by linearly mapping the projection space into the motion capture system space. To ensure data

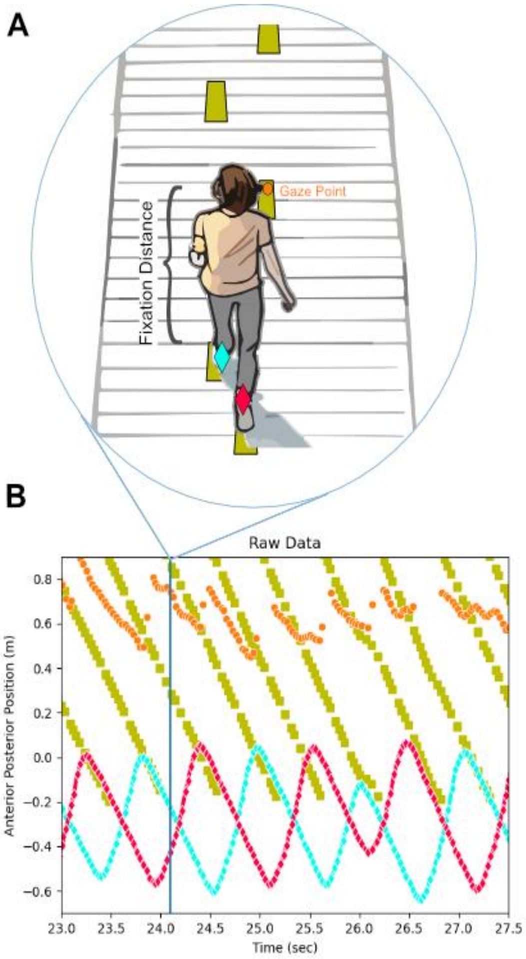

Figure 6-4: A. Diagram of the target stepping task. Stepping targets (in yellow) were projected onto the treadmill, Gaze point (Orange Dot) was calculated based on the eye tracking data. Fixation distance was defined as the distance between the head and the gaze point. Blue and Red diamonds are the calcaneus markers. Shapes and colors match scatterplot in B. B. Scatterplots showing the raw fixation data. Time is on the x axis and Anterior-Posterior distance from the participants head is on the y axis. The yellow squares are the stepping targets. The diamonds are the left (blue) and right (green) heel markers. The orange dots are individual gaze points. The diagram in A is a rough estimation of what is happening at the time point marked by the vertical line in B.

quality, a unique linear mapping was created for each participant using a projection calibration recording with a consistent static projected grid.

Data Alignment: Data between the target locations and motion capture during the step reaction time and target stepping tasks were sampled at 100 Hz. They were aligned using the motion capture system frame numbers which were streamed in real-time to the MATLAB program recording and projecting the targets. Gaze data were sampled at 200Hz and aligned to the motion capture system by aligning the nearest timestamps. Gaze data was manually clipped for the oculomotor testing to include individual trials.

Correlations: To test for confounding variables that may affect the outcome measures and to provide insights for future investigations, Pearson correlations were computed with demographics (Days to Recover), balance testing (only during eyes closed, on foam condition and oculomotor (total time and number of fixations) as the predictors and step error as the predicted variable.. A Bonferroni correction was used to control for multiple comparison testing (4 comparisons made with corrected p values reported).

Results

Visual Fixation Location: Individuals post-concussion look at the same place as matched controls

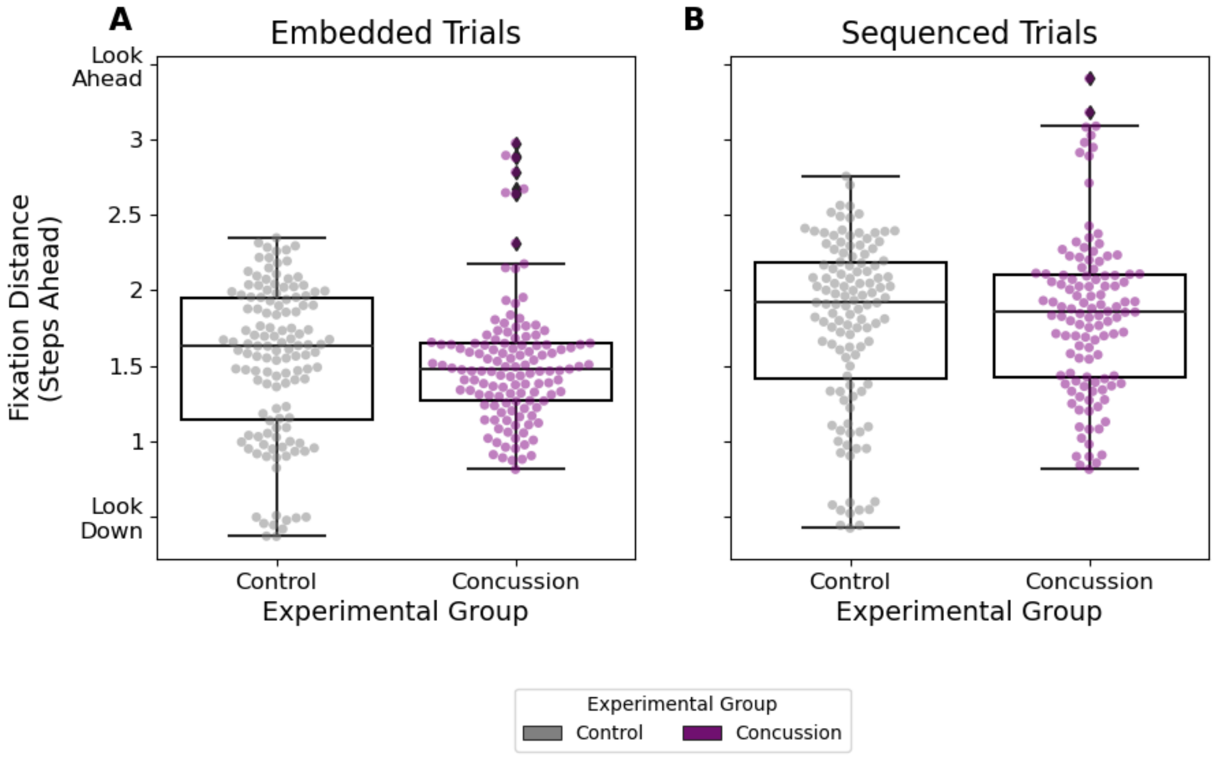

Figure 6-5: Box plots of the fixation distance during the embedded stepping task trial blocks (A) or the sequenced stepping task trial blocks (B). Data points represent individual trial blocks for each participant (10 points per participant in each graph).

To examine whether people recently medically cleared from a concussion exhibited altered visual fixation locations, two linear mixed models were performed. We found no significant differences in fixation distance between the experimental groups during the embedded trials (p=0.9, Figure 6-5A) nor the sequenced trials (p=0.8, Figure 6-5B).

Visual Reliance: Individuals post-concussion rely on vision the same amount as matched controls

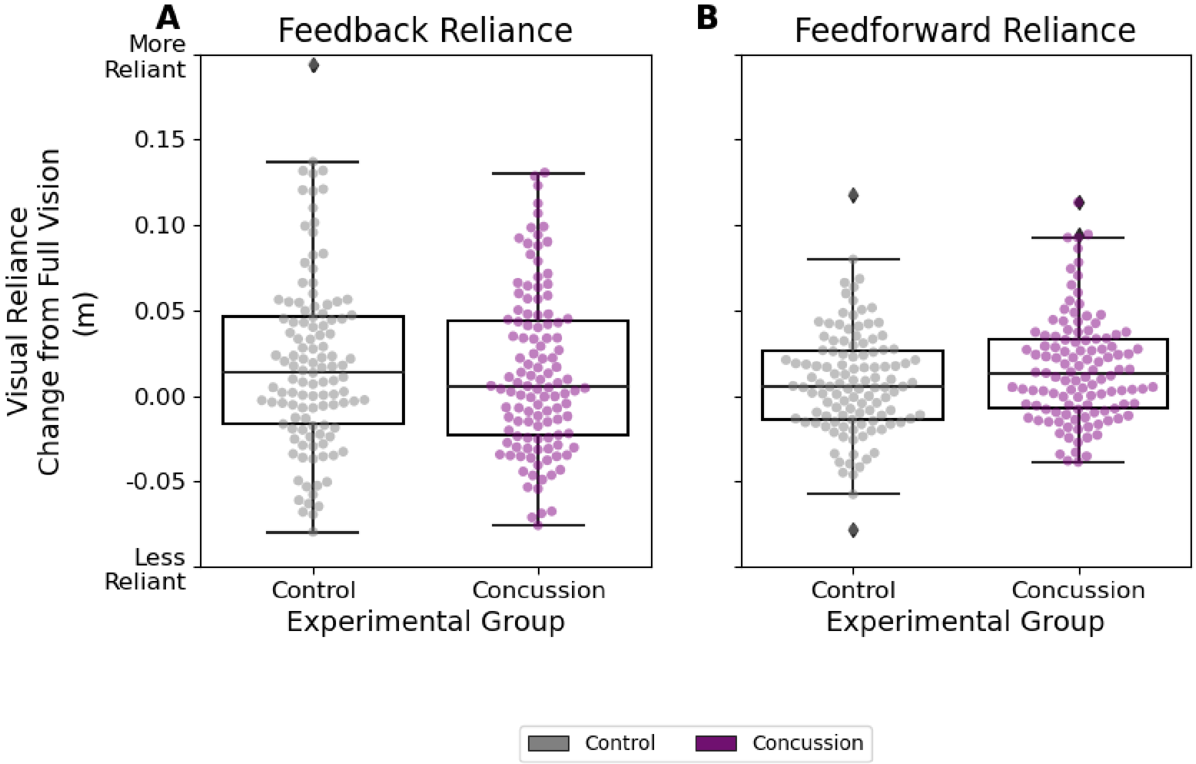

Figure 6-6: Boxplots of feedback (A) and feedforward (B) visual reliance. Individual points represent single trial block performance from each trial block of each participant (ten per participant)

To examine whether people post-concussion exhibited altered visual reliance, two mixed linear models were performed. There were no significant fixed effects for the experimental group, neither for Feedback Reliance (p=0.67, Figure 6-6A) nor Feedforward Reliance (p=0.33, Figure 6-6B).

Visuo-locomotor learning: Individuals post-concussion decreased their step error and increased their fixation distance similarly to matched controls

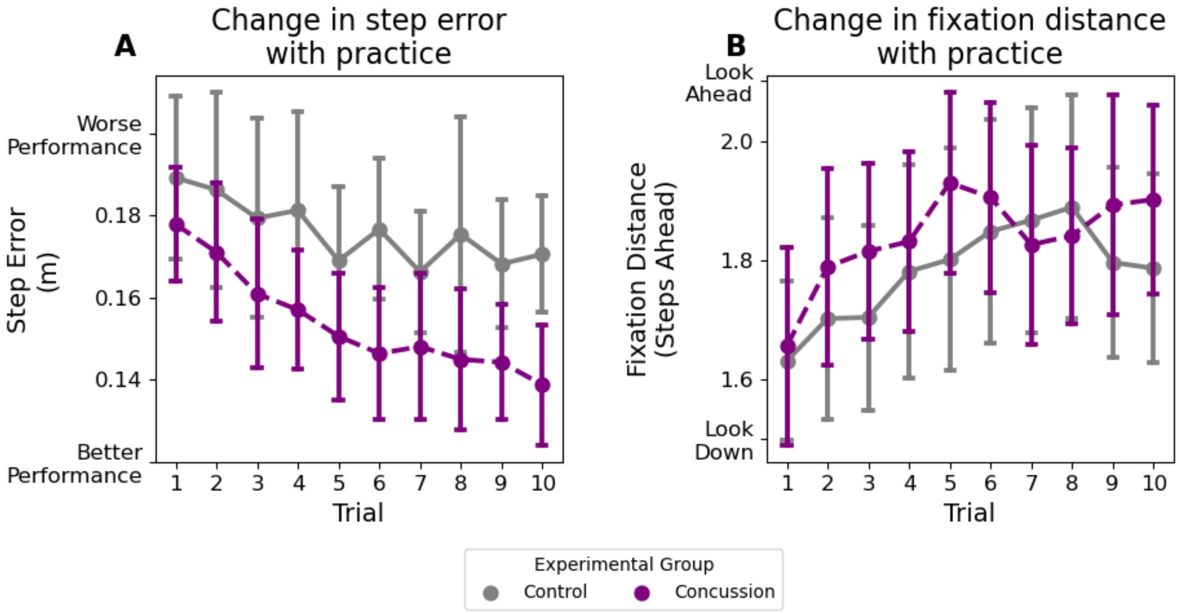

Figure 6-7: Changes in step error (A) and fixation distance (B) across trial blocks. We see both groups consistently decreased their step error and increased their fixation distance with practice. Error bars represent standard error for each trial block.

During the sequenced stepping trials, there was a significant effect of trial number, on both step error (p<0.001, Figure 6-7A) and fixation distance (p = 0.002, Figure 6-7B). However, there was no significant effect of the experimental group on step error (p=0.82) or fixation distance (p=0.77), in line with the visual fixation location results above. When examining visuo-locomotor learning, there were no significant interaction effects between step error (p=0.1) or fixation distance (p=0.88). Though individuals post-concussion improved their step error more, and for longer, than matched controls.

Baseline Tests: Persistent oculomotor and balance deficits when under enough cognitive load.

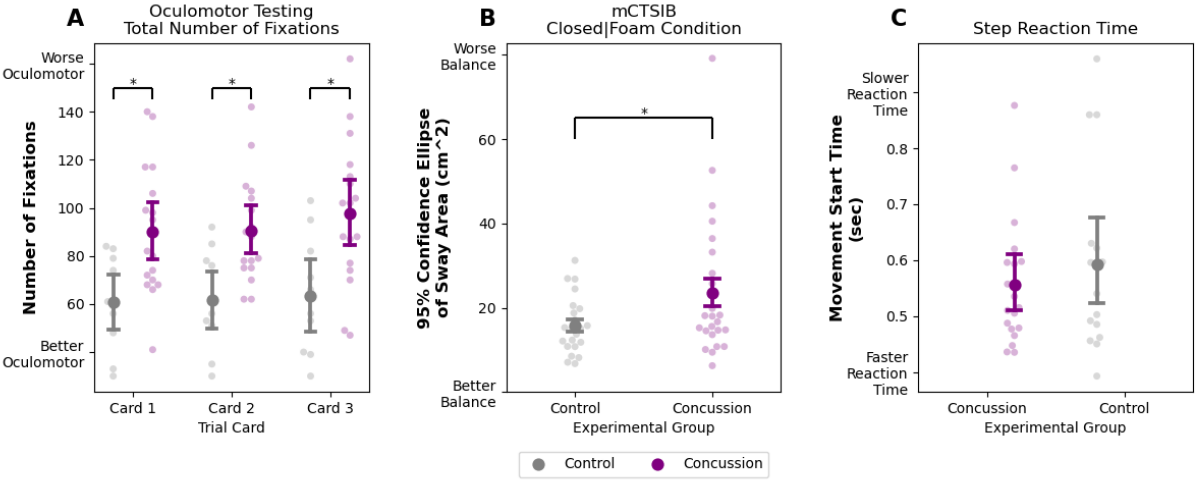

Figure 6-8: A. Mean and Standard Error of the number of fixations performed during the oculomotor testing. We see individuals post-concussion (purple) made significantly more errors than matched controls (gray). Individual data points represent individual trial data per participant (2 per participant). B. Mean and Standard Error of the 95% confidence ellipse of sway area during the eyes closed and standing on foam condition. We see significantly larger area of sway (worse balance) among individuals post-concussion. Data points represent individual trials per participant (two per participant). C. Mean and Standard Error of step reaction time. We see no significant difference between the two groups. Individual datapoints represent the average of all step reaction trials per participant (one per participant).

We found significant differences between the experimental conditions for both oculomotor testing (Figure 6-8A) and balance testing (Figure 6-8B), but not for step reaction time (Figure 6-8C).

For oculomotor testing, there was a significant difference between groups for the number of fixations (p=0.03, Figure 6-8A) but not for total performance time (p=0.09) or number of errors (p=0.83). Individuals post-concussion took longer on average to complete each trial and made significantly more fixations to complete the task. A ceiling effect may have limited the results in the number of errors, as participants in both groups rarely made any errors. There were no significant interaction effects, suggesting that the increased difficulty of the trial cards did not differentially impact individuals post-concussion.

For balance testing, there were significant interaction effects between the experimental group and visual condition (p=0.004) and the experimental group and surface (p=0.003). A pairwise Tukey test found a significant difference between groups only during the eyes closed, standing on foam condition (p=0.046, Figure 6-8B), with individuals post-concussion exhibiting worse balance in this condition.

For the step reaction time, there was not a significant effect of the experimental group on movement start time (p=0.66, Figure 6-8C). However, the results are limited by a smaller sample size (only 5 matched pairs of participants).

Correlations: Stepping performance was related to days to recover.

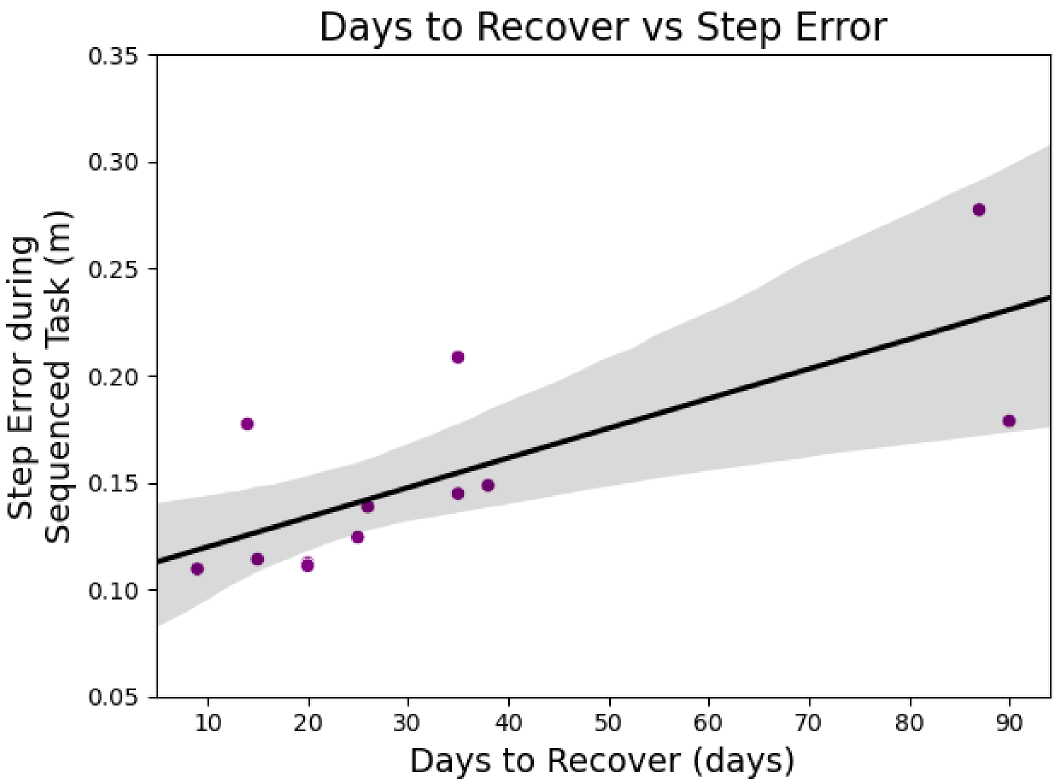

Figure 6-9: Regression plot of days to recover predicting step error. Only individuals post-concussion are included (purple). Gray shading represents standard deviation of the regression. Data points represent the average of all relevant trials for each participant (one per participant).

When stepping performance was correlated with demographic and baseline measures, we found a significant correlation between days to recover and step error (R^2=0.55, p corrected = 0.02). There were no significant correlations for oculomotor, balance, or step reaction time performance (p corrected > 0.5 in all cases).

Discussion

The present study examined whether visuomotor deficits are an underlying cause of the persistent gait deficits seen after medical clearance from a concussion (Wood et al. 2019; De Beaumont et al. 2009; Eagle et al. 2020). While our findings suggest that some deficits can persist beyond symptom recovery, we did not find evidence to support any of our three hypotheses. Specifically, individuals post-concussion did not exhibit altered visual fixation locations, altered visual reliance, or altered visuo-locomotor learning.

Visual Fixation Locations

Individuals who recently recovered from a concussion did not exhibit differences in where they looked when compared to matched controls. The finding were consistent during the embedded trials and sequenced trials. Therefore, the present study suggests that individuals post-concussion are collecting similar visual information to their non-concussed counterparts during a precision stepping task. Surprisingly, they did exhibit different oculomotor performance during the baseline testing. While oculomotor deficits should limit the ability of people to move their eyes to the necessary location, it may be that the visual fixation results were limited by task difficulty. Many of the deficits described in individuals post-concussion are only exhibited under cognitive load. In the present study, increasing cognitive load during oculomotor testing increased the difference between experimental groups. The target stepping task may not have been difficult enough to elicit differences in visual fixation locations. Future research should consider increasing the difficulty of the stepping task. Adding a dual task during walking has been shown to shift visual sampling away from the walking path and force greater sampling of feedforward visual information (Muller et al. 2023). Adding a similar dual task to the present study may add the cognitive load needed to elicit significant differences between groups.

Visual Processing and Reliance

When visual processing was examined by quantifying how much individuals rely on vision to guide their walking, we again found no significant differences between groups. Our results suggest that individuals post-concussion are processing the visual information they collect similarly to their non-concussed counterparts. However, the visual reliance exhibited by both groups here significantly differed from previous research in healthy adults (Chapter 5). Unlike the previous study where people significantly relied on both feedback and feedforward visual information, neither individuals post-concussion nor matched controls exhibited significant visual reliance during walking. This may be due to task design. Unlike the previous study, we embedded the visual probes into larger full-vision trial blocks to reduce the repeated errors previously reported. We also slowed the speed of the targets to avoid the task being too difficult for individuals post-concussion and to create a more generalizable situation. However, the effect of these changes in the present study may have made the stepping task too easy and led to a ceiling effect such that our protocol may not have had the sensitivity to quantify visual reliance. Therefore, future research should again look to make the task more difficult, by increasing the target speed, increasing the length of the probes, or introducing a dual task.

Visuo-Locomotor Learning

Finally, when visuo-locomotor learning was examined, we again found no significant deficits among individuals post-concussion. Both groups significantly decreased their step error and increased their fixation distance with practice, replicating previous findings from this lab (Cates and Gordon 2022). While both groups changed their step error and fixation distance, there were no detectable deficits in visuo-locomotor learning among individuals post-concussion. Individuals post-concussion actually decreased their step error significantly more than their matched controls, suggesting a possible enhancement to locomotor learning. Taken together, there is no evidence to suggest a visuo-locomotor learning deficit following a concussion.

Participant Characteristics

Participant characteristics may have affected the results of the present study. Our individuals post-concussion took longer than expected to recover, with a mean recovery time of 34.5 days. This is over twice as long as the typically reported timeline of about two weeks (McCrea et al. 2013). The time to recover was significantly correlated with stepping performance, suggesting that more significant injuries may have led to worse performance. Similar correlations between gait deficits and time to recover have been reported during the acute stages of the concussion (Millichap, 2015). Therefore, our results suggest that time to recover should be examined in future studies as a possible mitigating factor for post-recovery symptoms.

Future Directions: Proprioception

While future research is needed to confirm the results of the present study, our findings suggest that gaze behavior is not an underlying mechanism behind persistent gait deficits. While are a number of other possible mechanisms beyond visual deficits, such as motor execution or vestibular deficits, which may be behind the persistent gait deficits, we contend that deficits in proprioception are the next likely candidate to be investigated. Similar to vision, proprioception is a core sensory system for informing and controlling walking (Roden-Reynolds et al. 2015) and has been shown to be disrupted during the acute stages of a concussion (McPherson et al. 2019; Subbian et al. 2016). If these proprioceptive deficits persist beyond return to play designation, they could disrupt locomotor control strategies. Training proprioception can also improve motor control in healthy athletes (de Vasconcelos, Cini, and Lima 2020) and improve rehabilitation in clinical populations (Wang et al. 2021; Aman et al. 2014). Future research should therefore explore whether there are persistent proprioception deficits during walking to better understand the causes of persistent gait deficits.

Conclusions

The present study investigated whether the persistent gait deficits exhibited by people post-concussion are a result of visuo-locomotor deficits. Specifically, we examined if people post-concussion (< 2 weeks post symptoms returning to baseline) display altered visual fixation locations, visual reliance, or altered visuo-locomotor learning. We did not find evidence for any of the three hypotheses. While additional research is needed to ensure enough cognitive load was delivered to elicit post-concussion deficits, future research should also look for alternative explanations, such as proprioceptive deficits, which may underlie the persistent gait deficits.

Acknowledgements

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Chapter 7: A meta-view of gaze behavior changes

Introduction

The previous four chapters describe novel experiments exploring how gaze behavior, both where people look and how much they rely on vision, changes with motor learning or following a concussion. This chapter will take a meta-analytical approach to combine the results of these four chapters. Meta-analyses are often used to increase the statistical power and the precision of a specific result. They also can help identify patterns and relationships that may not be apparent in individual studies (Goh et al. 2016), developing new theories or strengthening existing ones. The present chapter will therefore combine the results of the four studies with the goals to:

1. Strengthen the conclusions on how fixation distance changes with locomotor learning.
2. Provide broader context for how visual reliance changes with locomotor learning.
3. Identify how different study designs may alter how people adapt their gaze behavior.

Locomotor learning and fixation distance

Due to the similarities in the methodologies between chapters 4, 5, and 6; the step error and fixation distance results can be directly compared without the need for transforming the original data. All studies utilized similar precision stepping tasks, where participants had to walk on the treadmill and accurately step on projected targets. I will focus on trials where the targets were fully visible and projected at 2x the speed of the treadmill. I will also split the experimental groups in Chapter 6, treating individuals post-concussion and their matched controls as separate studies for the purposes of this chapter. Four studies are included, specifically: Chapter 4 (as is), Chapter 5 (only full vision trials), Chapter 6 (only sequenced trials, individuals post-concussion), and Chapter 6 (only sequenced trials, matched control participants).

Step Error exhibit similar learning rates across all studies

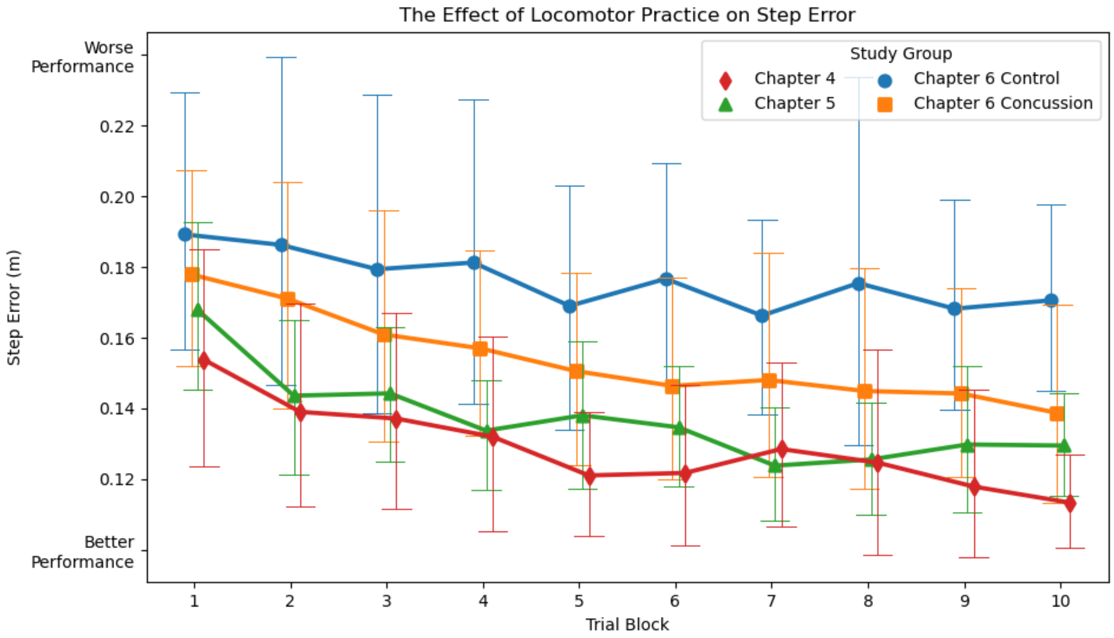

Figure 7-1: Line plots of the 4 experimental groups showing group mean and standard error of step error per trial block. We see all groups decrease their step error with practice.

When step error is plotted against trial block for each of the different studies, we can see some immediate similarities and differences (Figure 7-1). Using a mixed linear model with step error as the outcome measure; trial block, study, and their interaction as fixed effects; and subject as the random effect; I find a significant effect of trial block, but no significant effect of study or the interaction effect. Unsurprisingly, there is a significant effect of trial block ($p<0.001$) as participants did improve their stepping performance with practice (~0.4 cm per trial block). There was no significant effect of study group, with the greatest difference in average step error occurring between the matched control group from Chapter 6 and the participants of Chapter 4 (p=0.07). While study design likely created the variation in mean performance and learning rates, the overall trend is consistent and supports that target stepping is a trainable skill.

Despite the differences in study design, there was a consistent learning rate exhibited across all studies as evidenced by the significant effect of trial block and the lack of an interaction effect between study group and trial block. When the differences in study design are compared, the lack of significant differences in learning rates suggest two additional conclusions discussed below:

1. Sequence learning does not play a significant role in learning the target stepping task.
2. Individuals post-concussion do not exhibit reduced locomotor learning.

Sequence learning, or the process by which the brain learns to anticipate a repeating pattern of stimuli or responses, is well described in the motor learning literature (see Clegg, DiGirolamo and Keele 1998 or Babu 2020 for a review). Interestingly, while it is frequently observed in upper limb motor learning and was present in the finger coordination task presented in Chapter 3, it is rarely studied in the lower limb. While Choi and colleagues (Choi et al. 2015) demonstrated sequence learning in a target stepping task, none of the present locomotor studies found a sequence effect. Unlike Chapters 4 and 6, Chapter 5 did not use a repeating 6-step sequence of step lengths and instead presented the different step lengths in a random order. Similar to the lack of an effect of the catch trial described in Chapter 4, the lack of a different rate in Chapter 5 suggests that sequence learning mechanisms did not enhance motor learning when available. Overall, the combined results suggest that sequence learning does not play a major role in learning this target stepping task.

The lack of a difference in motor learning between individuals post-concussion and the other 3 groups also provides additional support for the lack of motor learning deficits following a concussion. As discussed in Chapter 6, preliminary evidence suggested that motor learning may be impaired following a concussion. I did not find any evidence of a motor learning deficit in Chapter 6, and the lack of differences in learning rates compared to the other studies of healthy young adults lends additional support for this conclusion.

Despite differences in study design, fixation distance increases with practice

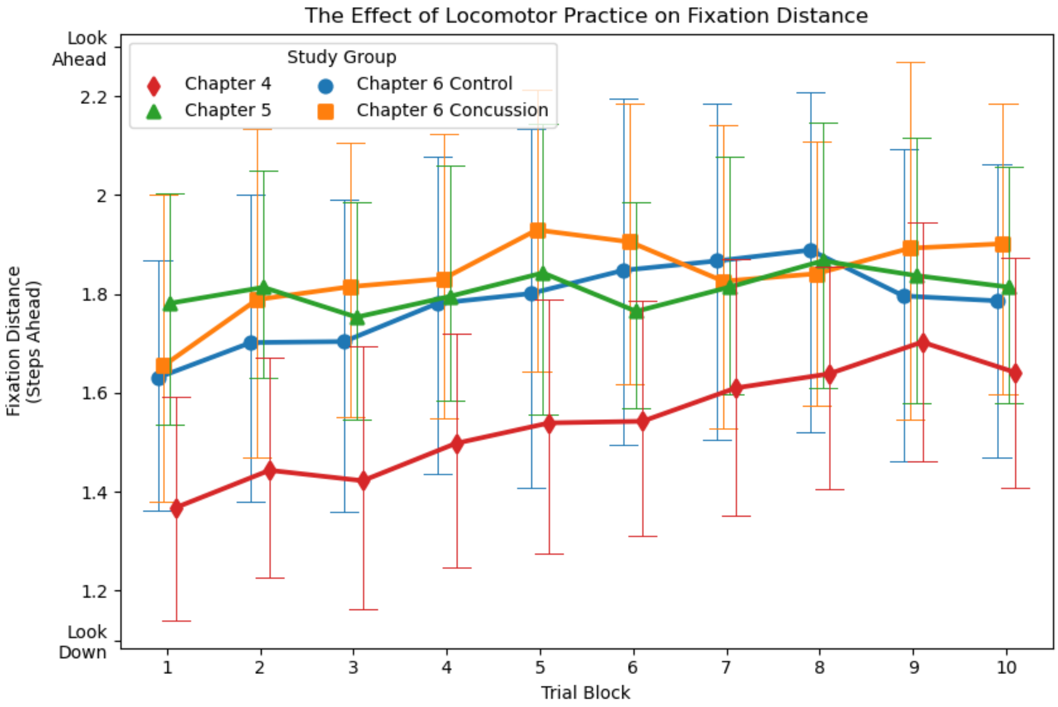

Figure 7-2: Line plots of the 4 experimental groups showing group mean and standard error for fixation distance per trial block. We see a general increase in fixation distance with practice, though with different amounts per group.

When we examine fixation distance across time, we can see that fixation distance increases with practice (Figure 7.2). We again used a linear mixed model with fixation distance as the outcome measure; trial block, study, and their interaction as fixed effects; and subject as a random effect.

We find significant fixed effects of both trial block and study, along with an interaction effect (p<0.001). Pairwise comparisons of the different studies revealed that the average fixation distance of Chapter 4 were significantly lower than the other 3 study groups (p<0.001 in all cases). Looking at the interaction effects, there was only a significant difference between the groups from Chapter 4 and Chapter 5, with participants in Chapter 4 increasing their fixation distance more over the course of the training period. As discussed in Chapter 5, this is likely a result of study design, with the intermittent probe trials significantly reducing the rate of change in fixation distance, possibly due to reduced confidence. Overall, the results support the initial findings of Chapter 4, that people increase their fixation distance as they improve at a novel walking task.

Motor learning and visual reliance

To aggregate the results of motor learning on visual reliance, I looked at the results of Chapters 3, 5, and 6. Because the measurement of visual reliance is task specific, the data from these chapters was transformed in order to compare the results. Cohen’s d effect sizes were calculated for the change in feedback and feedforward visual reliance with practice. For Chapters 3 and 5, I compared probe trial blocks from baseline and post training to calculate their effect sizes. For Chapter 6, to create a larger sample of probe trials, I averaged the visual reliance of the first 3 embedded trial blocks to create a baseline reliance, and the last 3 embedded trial blocks to create a post reliance. These baseline and post reliance measures were then compared to calculate the effect sizes for Chapter 6. As with step error and fixation distance, I treated individuals post-concussion and their matched controls as separate study groups for this analysis. The calculated Cohen’s d effect sizes and their 95% confidence intervals were then combined using a random effects model and weighted based on sample size to create a combined effect (for a description of fixed vs random effects models in meta-analyses, see Dettori et al. 2022). This new, combined effect is a better estimate of how motor learning impacts visual reliance across tasks.

Changes in feedback and feedforward visual reliance are task and individual dependent

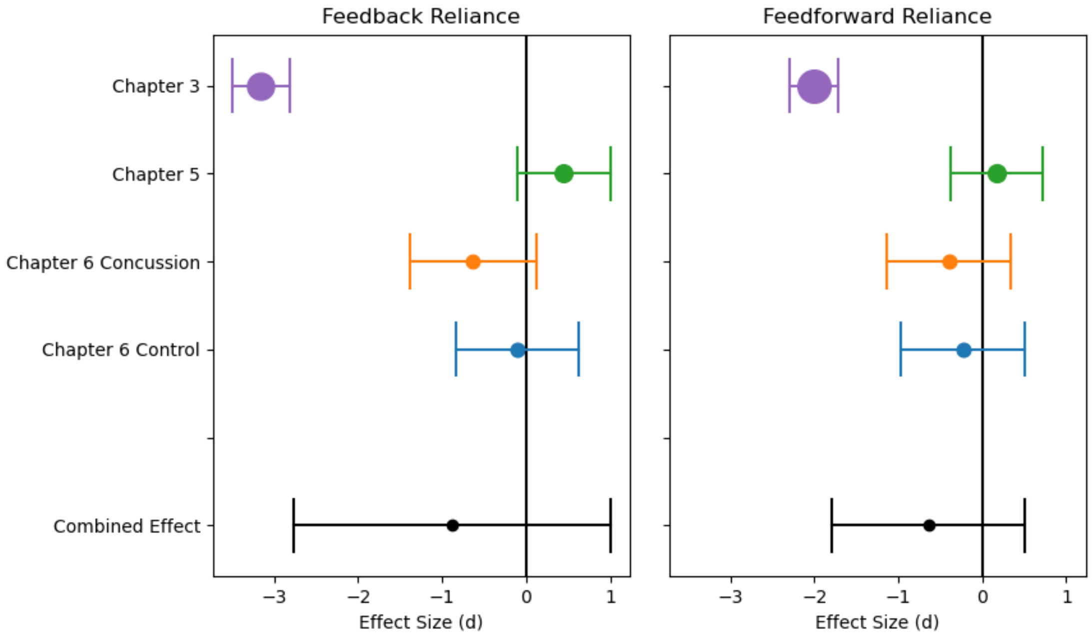

Figure 7-3: Forest plots of feedback (left) and feedforward (right) visual reliance changes. Positive numbers indicate an increase in reliance after training, negative numbers represent a decrease in reliance. size of the dot represents the weight of the study in the combined effect size while error bars are 95% confidence intervals for the effect size.

When we plot the feedback and feedforward reliance effect sizes, we find motor learning does not significantly reduce feedback nor feedforward visual reliance, though inter-study variance limits the overall effect (Figure 7-3). The largest change in visual reliance came from Chapter 3 with the finger coordination task. There was a significant reduction in both feedback and feedforward visual information in this study, unlike in the locomotor learning tasks. The result highlights the differences between a typing task and a walking task from a motor control standpoint and suggests typing may be less visually dependent, especially after some practice.

When we focus on the locomotor learning tasks, there is still a lot of variation between the results of Chapter 5 and Chapter 6. Task design may explain this difference with Chapter 6 utilizing shorter, embedded probes compared to Chapter 5. The long probe periods in Chapter 5 may have led to repeated errors (see Limitations in Chapter 5) which may have inflated the visual reliance scores. In contrast, the slower speed of the targets and the short probes may have deflated the visual reliance scores of Chapter 6, as participants in either group exhibited little reliance throughout the study. Future research is likely needed to better understand how feedback and feedforward visual reliance change with practice, particularly in relation to locomotor practice.

Conclusion

In general, the results of the meta-analysis presented here agree that fixation distance increases and step error decreases with practice, though there is not a consistent effect of practice on visual reliance. The change in fixation distance with practice provides additional detail into the role of gaze behavior throughout the motor learning process. While there are some differences evident due to the different study designs, the consistency of this result is significant, suggesting little-to-no effect of sequence learning or concussion on target stepping performance and fixation distance. In contrast, the effect of motor learning on visual reliance was significantly impacted by task, with visual reliance significantly reducing during the online learning task, and either increasing (Chapter 5) or decreasing (Chapter 6) with locomotor learning. More research is therefore needed to understand what may be driving these effects to determine the true impact of locomotor learning on visual reliance.

Chapter 8: Conclusions, clinical implications, and future directions

The research presented here first explores how gaze behavior changes with motor learning and then applies this knowledge to explore one possible mechanistic theory for why people post-concussion exhibit persistent gait deficits. In this final chapter, I will begin by providing a brief summary of my work and provide alternative perspectives to consider for each conclusion. I then present the clinical implications of this work. Throughout, I discuss outstanding questions and how they may be tested in the future.

Summary of work

The research presented here describes how gaze behavior changes in response to motor and in particular locomotor, learning along with how gaze behavior is impacted following a concussion. In short, I find:

1. Fixation distance increases with locomotor learning.
2. Visual reliance may or may not change with motor learning, dependent upon both task and individual characteristics.
3. Following recovery from a concussion there are no persistent gait deficits in gaze behavior during walking.

Fixation distance increases with locomotor learning

As captured in Chapter 7, fixation distance consistently increased with practice of the novel precision stepping task. While there was some variation due to task design (such as the inclusion of visual probes or not) and participant (post-concussion or healthy young adult), there was a clear underlying trend of fixation distance increasing and step error decreasing with locomotor practice. These results are in line with previous literature in the upper body (Sailer et al. 2005, Safstrom et al. 2014, Vieluf et al. 2015, Perry et al. 2020) and extend the work on walking (Kopiske et al. 2020, Muller et al. 2023) learning tasks. Additionally, unlike previous walking studies, the changes in both locomotor performance and fixation distance persisted across trial blocks. This may have to do with the continuous nature of the task used here, such that every step a participant took within a trial block must be guided to a target. Overall, the results confirm that fixation distance increases with locomotor learning.

Alternative perspective: Fixation distance vs fixation timing

While the present work focuses on fixation distance based on gaze location, one alternative perspective is a focus on fixation timing. Rather than the emphasis being on how far ahead an individual is fixating, it may be more fruitful to focus on time. Cognitive processing time may be the main driver of where someone looks in order to ensure they have enough time to process and react to the visual information they collect. Dominguez-Zamora and colleagues (2018) have shown that the timing relationship between fixations and steps relates to stepping performance, especially in uncertain environments. The present work does present toe-off and heel-strike intervals (Chapters 4 and 5) to include some of this information. However, because all the studies presented kept the target and walking speeds constant, the time and distance are relatively equal, with any changes coming primarily from changes in step length. While many studies (including those presented here) largely control for the difference between fixation distance and timing by setting the gait speed, whether the brain is optimizing for distance or time should be considered in future investigations.

Changes in visual reliance from motor learning may be task dependent

Unlike changes in fixation distance, changes in visual reliance from motor learning appear to greatly depend on the task being performed. In the online learning task (Chapter 3), participants were not reliant on feedback or feedforward visual information to learn the task, and motor learning significantly reduced their reliance on visual information to perform the task. In contrast, during the locomotor learning tasks, participant visual reliance either increased (Chapter 5) or decreased (Chapter 6). While the methods of probing visual reliance during walking may explain some of this variation, the large dichotomy between the online task (Chapter 3) and the walking tasks (Chapters 5 and 6) suggests that there may be different visual reliance processes for typing vs walking.

Alternative perspective: Central vs peripheral vision

While most eye tracking is done with central vision, there is evidence that much of the visual information used to control walking is gathered through peripheral vision (Franchak and Adolph 2010, Marigold 2008). The act of walking may actually increase peripheral awareness (Benjamin et al; 2018, Cao and Handel 2019; Reiser et al. 2022), possibly by increasing pupil size (Vilotijevic and Mathot 2022). In motor learning, Perry and colleagues (2020) demonstrated an increased use of peripheral vision from practicing a reaching task. As discussed in Chapter 5, a shift towards using peripheral vision would allow central visual fixation distance to increase while reliance on feedback visual information also increases. Additionally, preliminary evidence suggests peripheral awareness is not impaired following a concussion (Jenerou et al. 2018), in line with the lack of a difference in visual reliance found in Chapter 6. Peripheral vision should therefore be considered when examining how the role of vision changes with locomotor learning.

Next question: What role does peripheral vision play in locomotor learning?

Given that peripheral vision likely plays a significant role in guiding gait and that peripheral awareness is enhanced during walking, the shift in fixation distance may be explained by a shift from central to peripheral visual processing. Future research could look to quantify how peripheral visual processing changes with locomotor learning by scoring stepping performance only on targets that were never fixated upon (similar to the reaching study performed by Perry et al. 2020).

Gaze behavior does not change following a concussion

Surprisingly, my research found no differences in gaze behavior between individuals who recently recovered from a concussion and matched controls. The result is even more surprising given there were significant differences in balance and oculomotor performance. Counter to my hypothesis, visuo-locomotor performance was unchanged among individuals who recently recovered from a concussion. Visuomotor control may not, therefore, be disrupted in people post-concussion, at least during the target stepping tasks presented here. While a different methodology than proposed by Eagle and colleagues (2020), I still expected gaze behavior changes between the groups, especially considering both groups exhibited the characteristic increase in fixation distance with practice. Given this result, it is important to consider that vision may not be an underlying mechanism of the persistent gait deficits following a concussion.

Alternative perspective: Vision and proprioception

While Chapter 6 explores whether changes in gaze behavior are an underlying mechanism for the persistent gait deficits reported after recovery from a concussion, it is not the only possible mechanism. As discussed in Chapter 6, proprioception also plays a significant role in controlling walking (Roemmich et al. 2016) and is also disrupted during the acute stages of a concussion (Subbian et al. 2016; McPherson et al. 2019). When controlling movement, vision often acts to confirm and enhance the signal that proprioception initially provides (Roemmich et al. 2016). Similar to vision, training proprioception improves locomotor recovery among gait deficient populations (Aman et al. 2014; Wang et al. 2021) and may provide similar benefits among individuals post-concussion. Therefore, proprioception should be considered as part of future investigations into the recovery from a concussion.

Next question: What is the relationship between proprioception and vision in informing locomotor control?

While vision is the focus of the present dissertation, as discussed, proprioception presents a plausible alternative mechanism to explain the persistent gait deficits post-concussion. Therefore, exploring proprioception may provide novel insights into both the persistent gait deficits and more generally into the locomotor learning process. A future experiment may test proprioception by having individuals learn and reproduce a gait pattern (such as the sequence of step lengths used in chapters 4 and 6) without the use of visual feedback. Charting a person’s ability to use proprioception alone, and the accuracy of their proprioception during walking, may help optimize future movement training and rehabilitation approaches.

Clinical Implications

There are two main clinical implications of the research presented here: Implications for gaze training as a movement rehabilitation intervention and implications for the treatment of individuals with a concussion.

Gaze training for movement rehabilitation

The present dissertation explores how gaze behavior changes with motor, and in particular locomotor, learning. The results suggest that fixation distance naturally increases as a consequence of the motor learning process, but changes in visual reliance following training are mixed. A few studies have presented preliminary evidence that gaze training may be beneficial for motor rehabilitation. Young and Hollands (2010) repeatedly reminded older adults about where to look while navigating intermittent precision steps, finding improvements in step placement with the repeated reminders. Gunn and colleagues (2019) tested a gaze training program for older adults with glaucoma, again finding improvements in step placement accuracy following training on where to look. The present dissertation provides some interesting context to these approaches. First, with adults performing a typing task, we did not find that dictating where people looked effected learning rates. Second, we found fixation distance to naturally increase with locomotor learning, suggesting that the overall practice effects of walking provide natural benefits toward shifting gaze behavior. These two results suggest that gaze training protocols may not provide the benefits they suggest, as people may naturally look where they should based on their current ability and environment. Directing this gaze does not appear to accelerate motor learning. That said, given the success of these protocols, and the mixed results on locomotor learning and visual reliance presented here, there may be a different mechanism at play. I propose that gaze training protocols are more about training participants where to direct their attention and cognitive processing than they are about where they look. In that case, attention training may be useful for a broad range of gait-deficient populations, emphasizing what visual information to use, even if they don't need to emphasize where to look.

Implications for post-concussion care

For individuals with a concussion, there are a couple of different clinical implications. First, despite having reached the designated "recovery" point of symptoms returning to baseline as reported by a clinician, there was still evidence of balance and oculomotor dysfunction among individuals post-concussion. While standard clinical tests were used to probe these deficits, the outcome measures used were more precise than what is normally available in the clinic. Specifically, I used the center of pressure data instead of time for the balance testing and the number of fixations in addition to time and number of errors for oculomotor testing. Because the deficits were only apparent with the more precise measures, clinicians may need to incorporate more sensitive tests into their determination of return to play. Technological advancements may help this, as low-cost force plates (such as the Wii balance board) are being shown to provide reliable center of pressure evaluations of balance (Quijoux et al. 2020, Estevex-Pedraza et al. 2022). Eye-tracking technology has a longer way to go before achieving the same widespread accessibility, but automated calibration systems (such as is offered by Pupil Labs) and novel webcam-based eye tracking systems (Papoutsaki et al. 2016) suggest a future where the average clinic can conduct eye tracking based assessments.

Despite the persistent oculomotor and balance deficits found among individuals post-concussion, there were no visuo-locomotor deficits. Individuals post-concussion displayed the same fixation distance and step error as healthy controls, including a consistent change in each with locomotor practice. Given that, it is unlikely that fixation distance differences are a cause of the persistent locomotor deficits. While there were similarly no differences in visual reliance, the variation in results between Chapter 5 and Chapter 6 make me hesitant to make any definitive claims about how a concussion may affect visual reliance. As discussed in Chapter 6, both results may have been limited due to task difficulty (Fino et al. 2018), such that the target stepping task was not complex enough to elicit gait deficits (or similarly gaze behavior impairments). That said, when both results are taken together, they do not suggest that gaze behavior changes should be incorporated into the recovery process, though further testing, especially around visual reliance is needed.

Next question: How long do balance and oculomotor deficits persist post-concussion?

Given that Chapter 6 found persistent oculomotor and balance deficits 2 weeks post-recovery from a concussion, it is important to establish a timeline for how long these deficits may persist and what the recovery process may look like. While the present research did not exhibit gait deficits, previous literature has established impairments persisting for months after the concussion (Wood et al. 2019). Understanding if the balance and oculomotor deficits similarly persist would provide additional information on the recovery process from a concussion and would help design effective therapeutic interventions to improve recovery.

Final Thoughts

The present dissertation explores how gaze behavior, specifically where people look and how much they rely on visual information, changes with motor learning and following a concussion.

While there were clear changes in fixation distance following locomotor learning, changes in visual reliance and following a concussion were less clear. Together the studies characterize the process of visuomotor learning during walking and provide a strong foundation for further investigations into the accompanying sensory changes. The results also begin to narrow possible causes of the persistent gait deficits reported following recovery from a concussion. Future work should aim to characterize the role of peripheral vision in locomotor learning and the relationship between proprioception and vision in the control of walking.

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