RESEARCH ARTICLE

Control of Movement

Don't watch your step: gaze behavior adapts with practice of a target stepping task

Alexander Cates[1] and Keith E. Gordon[1,2]

[1]*Department of Physical Therapy and Human Movement Sciences, Northwestern University, Chicago, Illinois and* [2]*Research Service, Edward Hines Jr. VA Hospital, Hines, Illinois*

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. This 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%, and 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 that participants increasingly used a feedforward locomotor control strategy with practice.

gait; gaze behavior; motor learning; motor control; locomotion

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 (1). When these close fixation locations are occluded or ignored, foot placement becomes more variable, reducing postural steadiness (2) and making foot clearance of obstacles (such as a curb) less likely (3). In contrast, fixations farther ahead are used to plan the immediate and upcoming steps and to confirm that one is walking toward their desired destination (4, 5). 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 (6, 7). 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 toward their feet and farther ahead to gather additional information (1, 8). When walking across rough terrains, [such as stepping across rocks (8) or uneven cobblestones (9)], where precise foot placement is required to maintain stability, individuals decrease their focus to ∼1.2 steps ahead (8). 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 (8). Similarly, older adults (10), individuals with an incomplete spinal cord injury (11), and individuals with developmental coordination disorders (12) all display gaze behavior fixations that are closer to their feet when compared with their 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 (13). 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 with the associated time window 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 (14). Specifically and in line with fixation distance, when the environment is more predictable the visual information window shifts earlier in time compared with 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 (15, 16). Such a progression has been found when learning to walk (7), catching a ball (17), and shooting a basketball (18). 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. Although several studies find gaze behavior to shift farther ahead when learning reaching or finger coordination (19–22), others find no change in fixation distance (23). In walking, the evidence is more mixed. Kopiske et al. (24) 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 et al. (25) found that fixation distance decreased with practice, though their study lacked specificity in fixation distance compared with 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%, and 120% of preferred step length) was embedded into the precision stepping task. Choi et al. (26) 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 with 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 toward how locomotor performance and gaze behavior are intertwined.

MATERIALS AND METHODS

Participants

Twelve 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

Table 1. *Demographic information*

n	12
Age, yr	22–31
Sex	8 women, 4 men
Height, m	1.74 ± 0.10
Step length, m	0.52 ± 0.07

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 is available in Table 1.

Experimental Setup

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

Motion capture.
We collect three-dimensional (3-D) 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 13 passive reflective markers on the participant to track their motion throughout the duration of the trial. Three noncollinear markers on the head-mounted eye tracker determined the headset viewing plane relative to the laboratory reference plane. The other 10 markers tracked the second, third, and fifth 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; 27). The headset uses infrared reflection to determine the two-dimensional (2-D) pupil location of each eye, and, following a calibration period, we transformed this data into a two-dimensional gaze point in the viewing plane. Gaze vectors were then determined using methods described by Matthis et al. (8), from which fixation points were defined as the location where the gaze vector intersected with the treadmill surface.

Stepping Task

During the stepping task, participants walked on the treadmill while stepping targets were projected onto the treadmill. 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 (2 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 the 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-min 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 (0.9 m/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 five sequenced trials, then a catch trial, and finally four more sequenced trials. During all sequenced trials, the targets appeared in the same, repeating, a six-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 et al. (26) 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 (28).

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 were 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 (100 Hz) more than 0.15 mm ($\sim$70°/s) in the x direction or 0.3 mm ($\sim$140°/s) in the y direction. In addition, 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 et al. (8). 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 m in front of the scene camera. The corners of the rectangle were defined by the intrinsic camera values (103° horizontal and 54° vertical) and the center was located 1 m 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 (8).

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 100 Hz 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 200 Hz 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 Fig. 1) and the treadmill surface fixation point along the plane of the treadmill (Fig. 1).
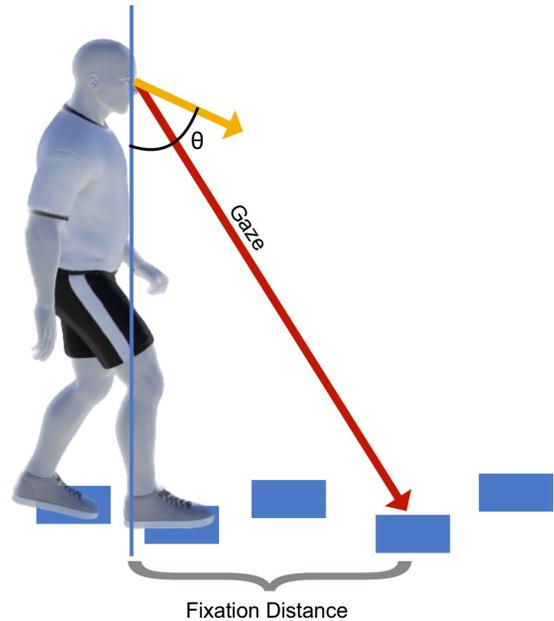

Figure 1. Diagram demonstrating the stepping task with head angle (θ) and fixation distance measurement.

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. Although 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 (Fig. 1).

Toe off interval.
The toe-off interval is defined as the time (in s) 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 s) 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 six 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 was on steps following an accurate versus 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

Processed data showing the locations of the left and right feet, the stepping targets and the fixation point on the treadmill are presented in Fig. 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 (Fig. 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 baseline versus 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 s to 1.80 s (290 ms total change). When 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) (Fig. 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 s, $P = 0.49$).

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

To determine how participants respond to an error step, a mixed linear model with subject as a random effect and
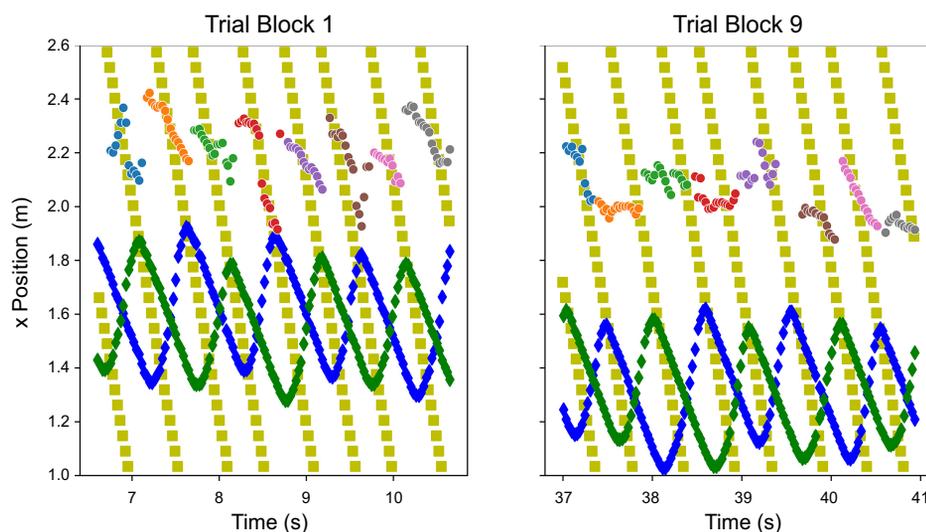

Figure 2. Data from one participant of the anterior-posterior position of the left (blue diamonds) and right (green diamonds) heel, stepping targets (yellow squares) and gaze location (colored dots, each color grouping is a unique fixation) through time. The figure demonstrates the hypothesized shift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

Step Error and Gaze Behavior Changes Across Trials

Figure 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 means ± SE. Results support step error decreasing while fixation distance and head angle increase (the participant looks farther ahead) with practice.
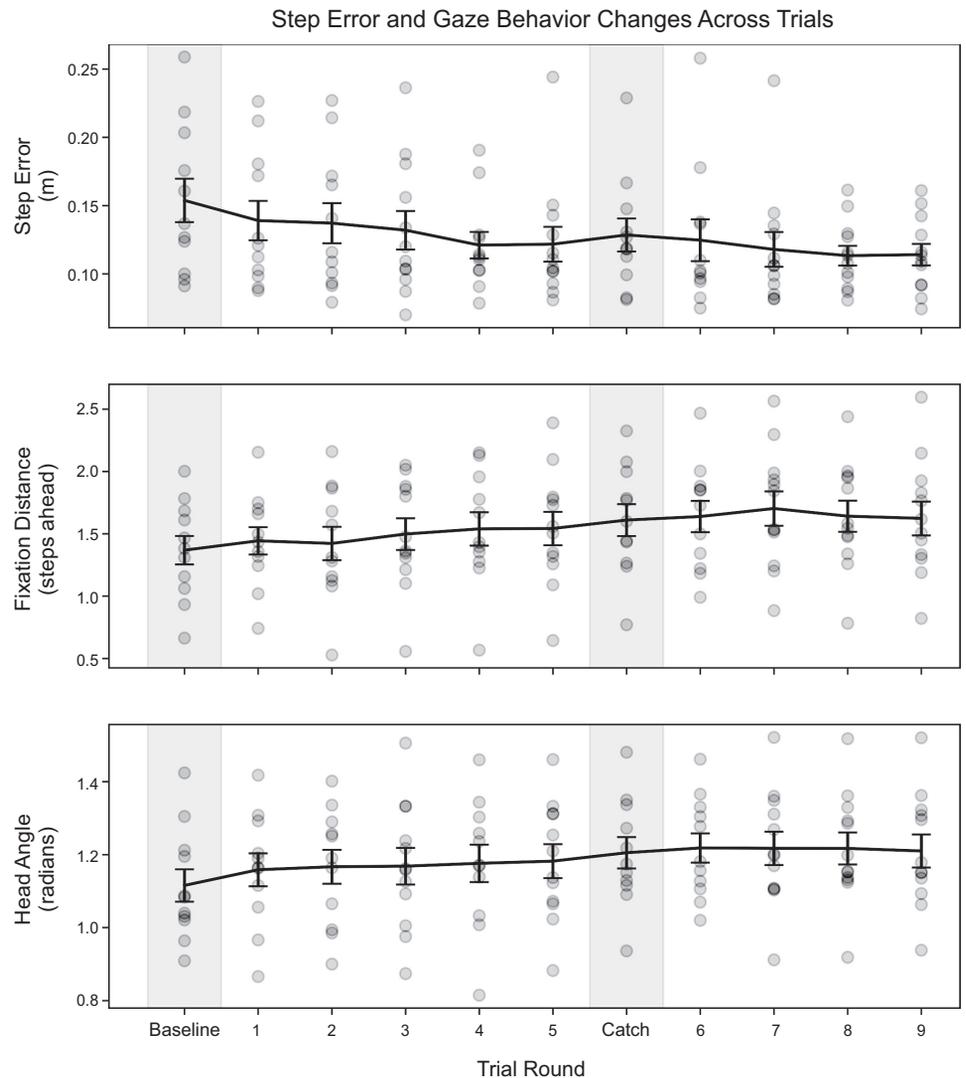
previous step accuracy as a fixed effect was performed to compare the fixation distance of a step following an error or accurate step. A significant change in fixation distance based on the previous step accuracy ($P < 0.001$) was found with an error on the previous step leading to a mean reduction in fixation distance of 0.08 steps (Fig. 5).

Participants Did Not Exhibit Learning within Trial Rounds

Although 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 ($P = 0.96$).

In addition, 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* (Fig. 6). To allow for any learning effects while minimizing the effect of step error, performance was grouped in six 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 fixated effects on fixation distance (Fig. 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 two 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
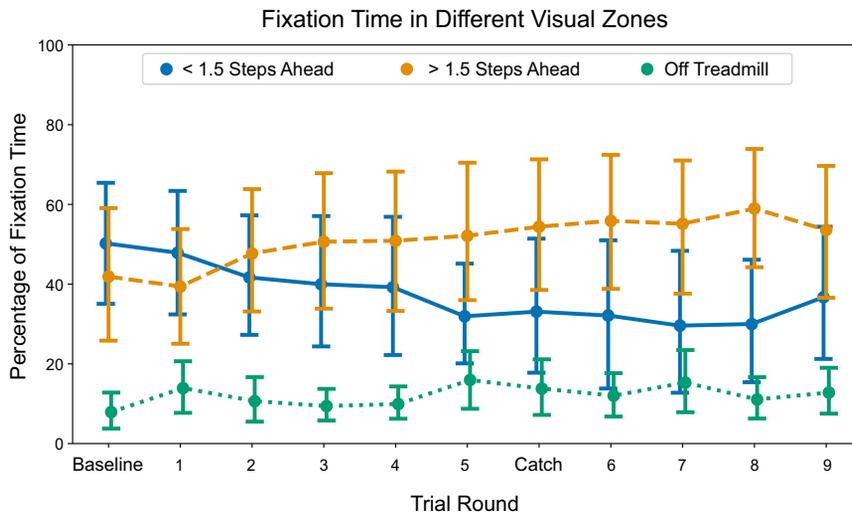
Fixation Time in Different Visual Zones

Figure 4. Error bar plot represent the percent of fixations directed toward 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 toward information greater than 1.5 steps ahead with practice, but that the participant consistently fixates in all three visual zones.

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 (15). 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.
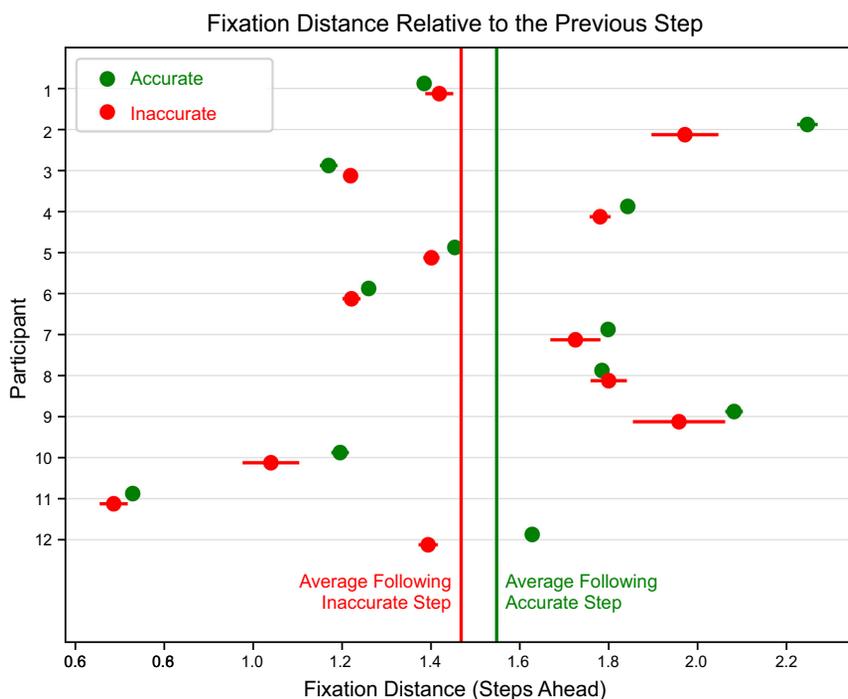
Fixation Distance Relative to the Previous Step

Figure 5. Means and SE 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.
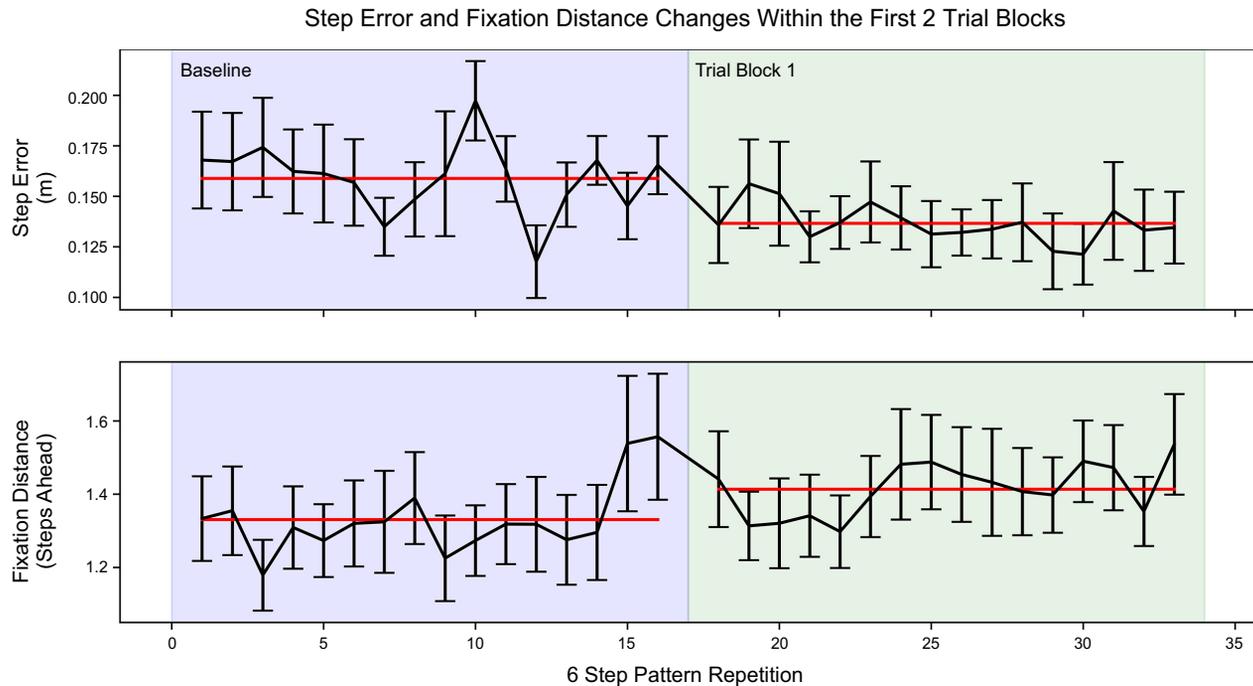
Step Error and Fixation Distance Changes Within the First 2 Trial Blocks

Figure 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 means ± SE. The results support the changes occurring between trial blocks (red lines) and less so within trial blocks (error bar plots).

Participants shifting their gaze farther ahead is in line with previous upper limb (19, 21) and walking (24) 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 in Ref. 21). However, as demonstrated in Fig. 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; Ref. 29). The changing fixation distance and locomotor control strategies may alternatively suggest an increased planning horizon (22, 30). 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 Fig. 4, although 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 in Ref. 19). 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. Although we expected both to revert toward 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 et al. (26), 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. Although most participants could tell that the prescribed step length changed, few were able to articulate

the pattern, even after 153 repetitions. In addition, the speed of the targets and the sequence employed in the present study were different than in the study by Choi et al., 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 the study by Choi et al. 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 the 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. Although 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 data set. 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 (∼1 cm 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. Although we do see a significant slope for fixation distance within the first two 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 is in contrast to the findings by Kopiske et al. (24) 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 versus one target every few steps in Ref. 24. Given this difference, the present study is more in line with reaching (19) and finger coordination (21) 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. Although it is likely that processing follows foveal vision, this is not a requirement (19). 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 (31). To consistently compare gaze behavior to task performance, we did not update task difficulty as participants improved. Although 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.

DATA AVAILABILITY

ACKNOWLEDGMENTS

GRANTS

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

A.C. and K.E.G. conceived and designed research; A.C. performed experiments; A.C. analyzed data; A.C. and K.E.G. interpreted results of experiments; A.C. prepared figures; A.C. drafted manuscript; A.C. and K.E.G. edited and revised manuscript; A.C. and K.E.G. approved final version of manuscript.

REFERENCES

1. **Patla AE.** Strategies for dynamic stability during adaptive human locomotion. *IEEE Eng Med Biol Mag* 22: 48–52, 2003. doi:10.1109/memb.2003.1195695.

2. **Koren Y, Mairon R, Sofer I, Parmet Y, Ben-Shahar O, Bar-Haim S.** Gazing down increases standing and walking postural steadiness. *R Soc Open Sci* 8: 201556, 2021. doi:10.1098/rsos.201556.

3. **Timmis MA, Buckley JG.** Obstacle crossing during locomotion: visual exproprioceptive information is used in an online mode to update foot placement before the obstacle but not swing trajectory over it. *Gait Posture* 36: 160–162, 2012. doi:10.1016/j.gaitpost.2012.02.008.

4. **Patla AE, Vickers JN.** How far ahead do we look when required to step on specific locations in the travel path during locomotion? *Exp Brain Res* 148: 133–138, 2003. doi:10.1007/s00221-002-1246-y.

5. **Hollands MA, Patla AE, Vickers JN.** Look where you're going!": gaze behavior associated with maintaining and changing the direction of locomotion. *Exp Brain Res* 143: 221–230, 2002. doi:10.1007/s00221-001-0983-7.

6. **Saeedpour-Parizi MR, Hassan SE, Baniasadi T, Baute KJ, Shea JB.** Hierarchical goal effects on center of mass velocity and eye fixations during gait. *Exp Brain Res* 238: 2433–2443, 2020. doi:10.1007/s00221-020-05900-0.

7. **Yamamoto H, Sato A, Itakura S.** Transition from crawling to walking changes gaze communication space in everyday infant-parent interaction. *Front Psychol* 10: 2987, 2019. doi:10.3389/fpsyg.2019.02987.

8. **Matthis JS, Yates JL, Hayhoe MM.** Gaze and the control of foot placement when walking in natural terrain. *Curr Biol* 28: 1224–1233.e5, 2018. doi:10.1016/j.cub.2018.03.008.

9. **Thomas NDA, Gardiner JD, Crompton RH, Lawson R.** Keep your head down: maintaining gait stability in challenging conditions. *Hum Mov Sci* 73: 102676, 2020. doi:10.1016/j.humov.2020.102676.

10. **Chapman GJ, Hollands MA.** Age-related differences in visual sampling requirements during adaptive locomotion. *Exp Brain Res* 201: 467–478, 2010. doi:10.1007/s00221-009-2058-0.

11. **Malik RN, Cote R, Lam T.** Sensorimotor integration of vision and proprioception for obstacle crossing in ambulatory individuals with spinal cord injury. *J Neurophysiol* 117: 36–46, 2017. doi:10.1152/jn.00169.2016.

12. **Warlop G, Vansteenkiste P, Lenoir M, Deconinck FJA.** An exploratory study of gaze behaviour in young adults with developmental coordination disorder. *Hum Mov Sci* 73: 102656, 2020. doi:10.1016/j.humov.2020.102656.

13. **Piras A, Lobietti R, Squatrito S.** A study of saccadic eye movement dynamics in volleyball: comparison between athletes and non-athletes. *J Sports Med Phys Fitness* 50: 99–108, 2010.

14. **Domínguez-Zamora FJ, Gunn SM, Marigold DS.** Adaptive gaze strategies to reduce environmental uncertainty during a sequential visuomotor behaviour. *Sci Rep* 8: 14112, 2018. doi:10.1038/s41598-018-32504-0.

15. **Franklin DW, Wolpert DM.** Computational mechanisms of sensorimotor control. *Neuron* 72: 425–442, 2011. doi:10.1016/j.neuron.2011.10.006.

16. **Franklin DW, Osu R, Burdet E, Kawato M, Milner TE.** Adaptation to stable and unstable dynamics achieved by combined impedance control and inverse dynamics model. *J Neurophysiol* 90: 3270–3282, 2003. doi:10.1152/jn.01112.2002.

17. **Hayhoe M, Mennie N, Sullivan B, Gorgos K.** The role of internal models and prediction in catching balls. Proceedings of the American Association for Artificial Intelligence 2005, p. 1–5.

18. **Oudejans RRD, van de Langenberg RW, Hutter RIV.** Aiming at a far target under different viewing conditions: visual control in basketball jump shooting. *Hum Mov Sci* 21: 457–480, 2002. doi:10.1016/s0167-9457(02)00116-1.

19. **Perry CM, Singh T, Springer KG, Harrison AT, McLain AC, Herter TM.** Multiple processes independently predict motor learning. *J Neuroeng Rehabil* 17: 151, 2020. doi:10.1186/s12984-020-00766-3.

20. **Vieluf S, Massing M, Blandin Y, Leinen P, Panzer S.** The role of eye movements in motor sequence learning. *Hum Mov Sci* 40: 220–236, 2015. doi:10.1016/j.humov.2015.01.004.

21. **Sailer U, Randall Flanagan J, Johansson RS.** Eye–hand coordination during learning of a novel visuomotor task. *J Neurosci* 25: 8833–8842, 2005. doi:10.1523/JNEUROSCI.2658-05.2005.

22. **Ariani G, Kordjazi N, Pruszynski JA, Diedrichsen J.** The planning horizon for movement sequences. *eNeuro* 8: ENEURO.0085-21.2021-21, 2021. doi:10.1523/ENEURO.0085-21.2021.

23. **Mathew J, Flanagan JR, Danion FR.** Gaze behavior during visuomotor tracking with complex hand-cursor dynamics. *J Vis* 19: 24, 2019. doi:10.1167/19.14.24.

24. **Kopiske KK, Koska D, Baumann T, Maiwald C, Einhäuser W.** Icy road ahead-rapid adjustments of gaze-gait interactions during perturbed naturalistic walking. *J Vis* 21: 11, 2021. doi:10.1167/jov.21.8.11.

25. **Koren Y, Mairon R, Sofer I, Parmet Y, Ben-Shahar O, Bar-Haim S.** Vision, cognition, and walking stability in young adults. *Sci Rep* 12: 513, 2022. doi:10.1038/s41598-021-04540-w.

26. **Choi JT, Jensen P, Nielsen JB.** Locomotor sequence learning in visually guided walking. *J Neurophysiol* 115: 2014–2020, 2016. doi:10.1152/jn.00938.2015.

27. **Pupil Labs.** Terminology. Pupil Labs Documentation. https://docs.pupil-labs.com/core/terminology/ [2022 May 17].

28. **Winter DA, Sidwall HG, Hobson DA.** Measurement and reduction of noise in kinematics of locomotion. *J Biomech* 7: 157–159, 1974. doi:10.1016/0021-9290(74)90056-6.

29. **Lehtonen E, Lappi O, Kotkanen H, Summala H.** Look-ahead fixations in curve driving. *Ergonomics* 56: 34–44, 2013. doi:10.1080/00140139.2012.739205.

30. **Bashford L, Kobak D, Diedrichsen J, Mehring C.** Motor skill learning decreases movement variability and increases planning horizon. *J Neurophysiol* 127: 995–1006, 2022. doi:10.1152/jn.00631.2020.

31. **Wilson RC, Shenhav A, Straccia M, Cohen JD.** The eighty five percent rule for optimal learning. *Nat Commun* 10: 4646, 2019. doi:10.1038/s41467-019-12552-4.