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RESEARCH ARTICLE

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

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Abstract
People use vision to inform motor control strategies during walking. With practice performing a target stepping task, people 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 changing visual fixation location is accompanied by a similar change in reliance upon visual information. Twenty healthy young adults practiced stepping on moving targets projected on the surface of a treadmill. Periodically, participants' visual reliance was probed by hiding stepping targets which 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. 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, 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 looking significantly farther ahead with practice ($p < 0.016$). Together, these results suggest that participants fixated on feedback information less. However, changes in fixation pattern did not reduce their reliance upon feedback information as 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.

Keywords Gait · Gaze behavior · Motor control · Visual reliance · Motor learning · Locomotion

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. 2020a, b), performing

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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 amount 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 cannot 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 et al. 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 genetics 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 a greater 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, 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 ± 0.1 m 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 (3 m × 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 × 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 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 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 (Fig. 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 et al. 2018; Sanchez et al. 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).

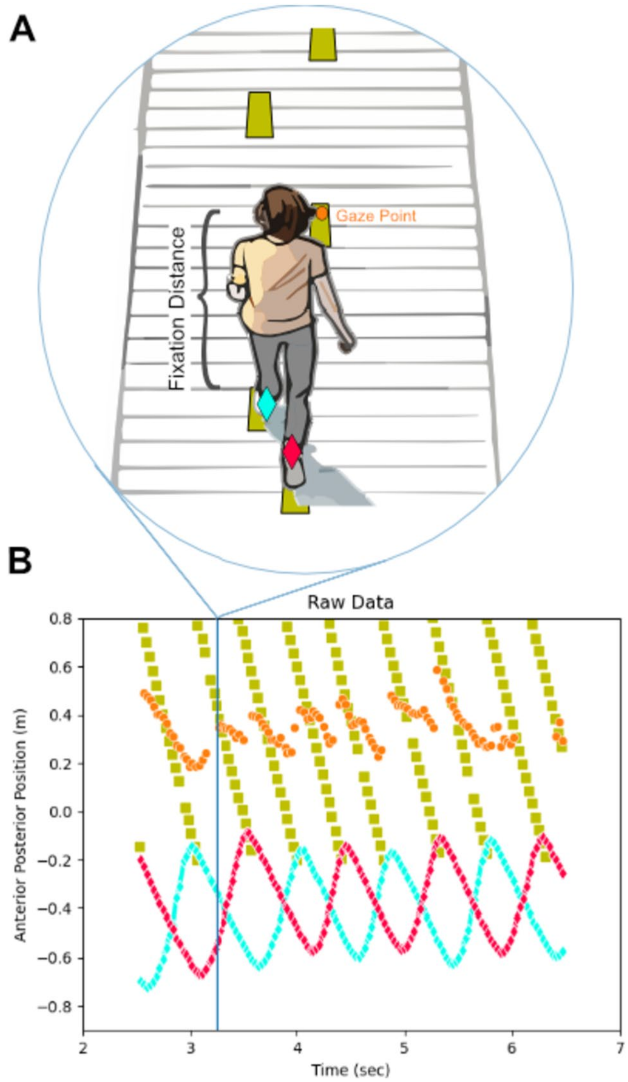

Fig. 1 **A** Diagram of the target stepping task. Stepping targets (in yellow) were projected onto the treadmill, gaze point (orange dot) was calculated based on the eye-tracking data. Fixation distance was defined as the distance between the head and the gaze point. Blue and red diamonds are the calcaneus 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

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, Fig. 2A) or less than 1.5 steps ahead of the participant (the no feedforward condition, Fig. 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 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-min 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 (Fig. 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

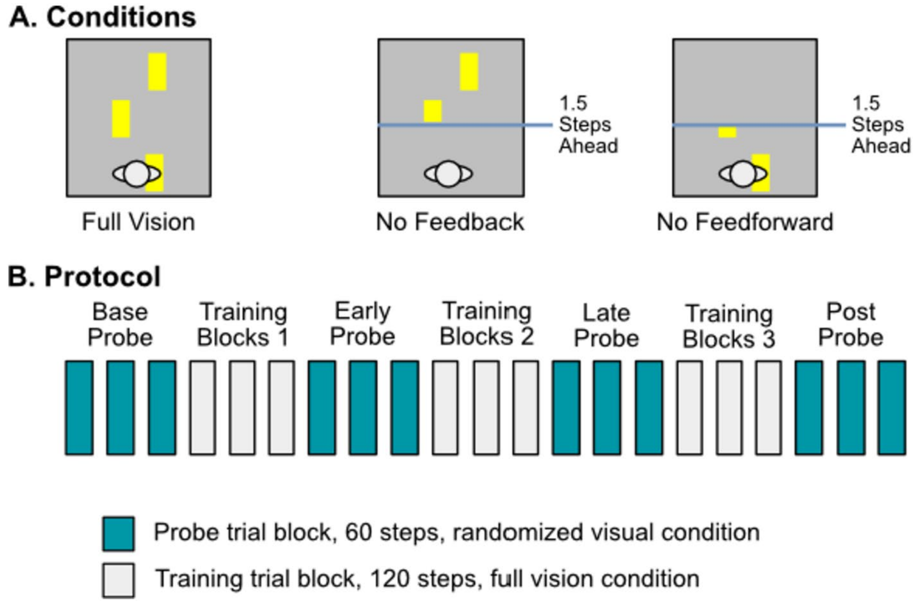

Fig. 2 **A** Aerial view of the treadmill, participant, and targets in the three different conditions. Note the image is not to scale. **B** Trial block outline

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 $1.55° \pm 0.81°$. 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 m 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 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. Representative data are available in Fig. 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 (Fig. 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 are 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 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. Equivalence testing was performed using a TOST test for all non-significant results with a boundary equal to half of the step error improvement made across full vision condition trials.

For all results, *p* values are reported in the results section. Complete results from the linear mixed models, including coefficients, test statistics, and confidence intervals are available in the supplementary information.

Results

Participants

Two participants had poor eye-tracking quality (majority of samples below 60% pupil detection confidence as provided by the Pupil Player software) and were removed from eye-tracking-based results (Figs. 3 and 5). However, because the primary result was based on motion capture data alone, both were included in the visual reliance analysis below (Fig. 4). Data from a representative participant are provided in Fig. 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

With practice of the full vision task, participants decreased their step error ($p < 0.001$, ~ 0.002 m per trial block) and looked farther ahead as indicated by significant increases in fixation distance ($p = 0.016$) but not head angle ($p = 0.109$, Fig. 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.

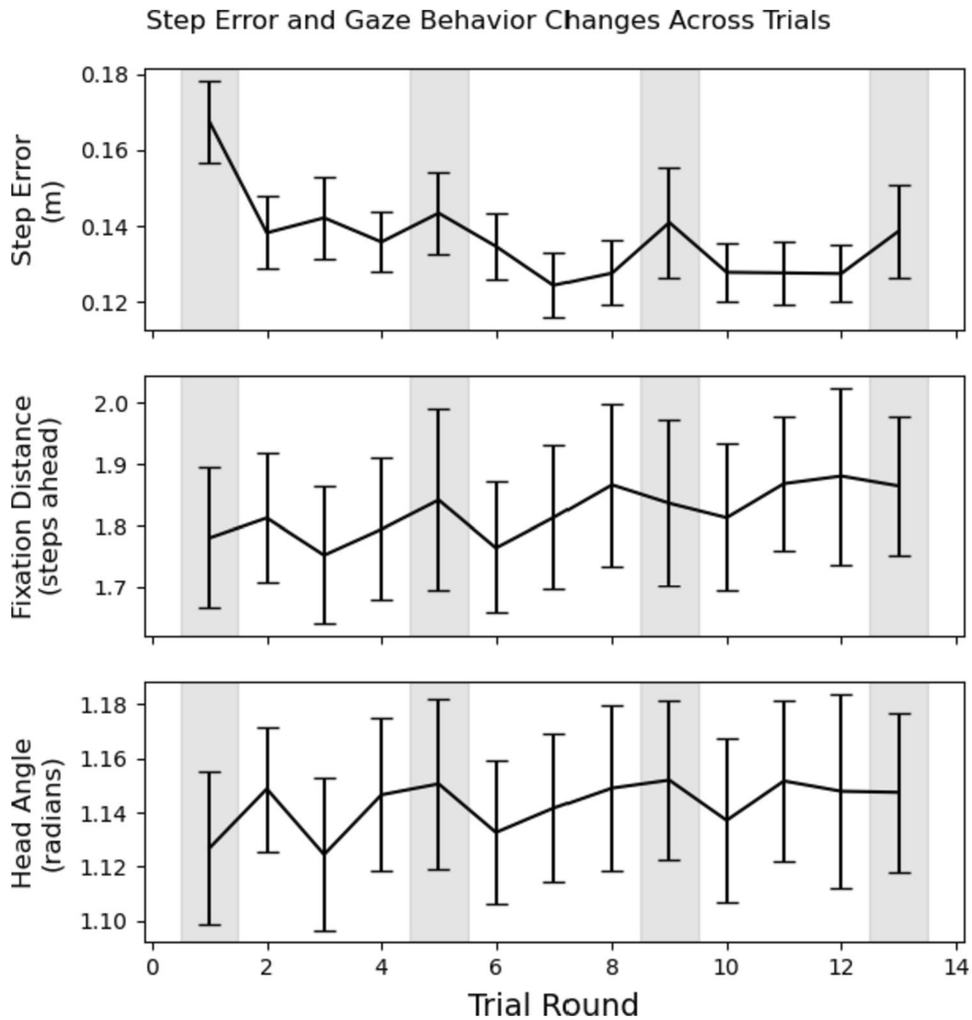

Fig. 3 Line plots showing mean and SEM across participants for step error (top), fixation distance (middle) and head angle (bottom) during the full vision trial blocks. Gray vertical bars represent probe blocks where the full vision trial may be in one of 3 trial numbers but were grouped for the graph here. The results show step error decreased while fixation distance increased with practice

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

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 (Fig. 5a). 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 ($p < 0.001$, Fig. 5b). 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 (Fig. 5c). 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 we compare the different visual conditions (Table 1), we see that participants performed worse in the no feedback and no feedforward conditions compared to full vision

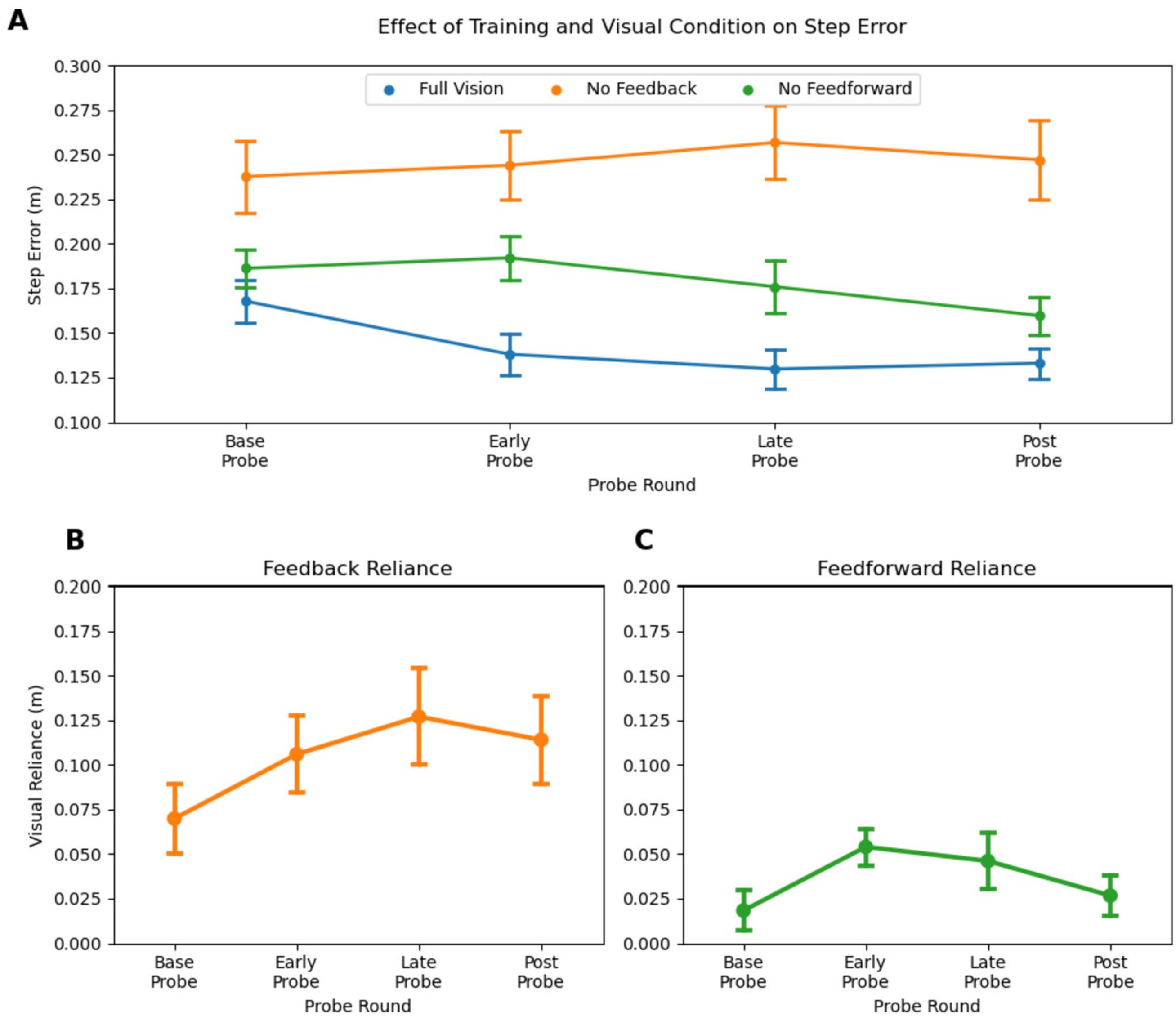

Fig. 4 **A** Mean and SEM across participants of step error during the four probe periods, split by visual condition of the probe. B and C show between participant mean and standard error of the computed feedback (**B**) and feedforward (**C**) visual reliance during the 4 probe block periods. Feedback 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

regardless of the amount of practice ($p < 0.001$, Fig. 4A). The interaction effect found a significant change in the reliance on feedback ($p < 0.001$) but not in the reliance on feedforward ($p = 0.49$) visual information. As seen in Fig. 4B and 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, Fig. 5A). They also changed their toe-off interval (Fig. 5B) and heel strike interval (Fig. 5C) significantly less in the no feedforward condition than the full vision and no feedback conditions, though they were directionally the same.

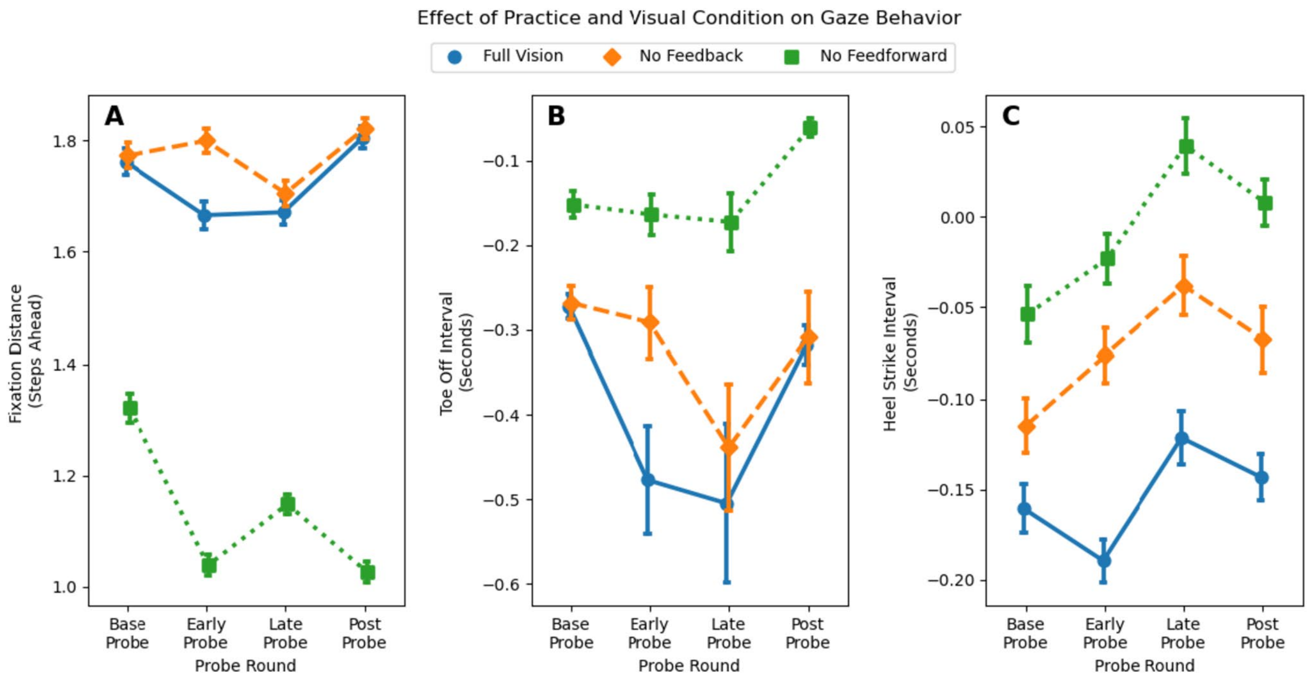

Fig. 5 Changes in gaze behavior during the visual probe conditions with practice. Line plots show the mean and standard error across participants for the fixation distance (**A**), Toe off interval (**B**) and heel strike interval (**C**) across probe blocks. The negative values in B and C suggest that toe off (**B**) and heel strike (**C**) occurred after the initial fixation started (**B**) or last fixation ended (**B**)

Table 1 Linear mixed-effects model results for assessing whether visual reliance changed with practice

	Coef	Std Err	Z	P	95% CI
Intercept	0.164	0.0010	17.216	0.000	0.145 to 0.183
Trial number (B_0)	– 0.002	0.000	– 4.036	0.000	– 0.003 to – 0.001
Visual condition (B_1) No FF vs FV	0.032	0.009	3.625	0.000	0.015 to 0.049
Visual condition (B_1) No FB vs FV	0.068	0.008	8.108	0.000	0.051 to 0.084
Trial number|Visual condition (B_2) No FF vs FV	0.000	0.001	0.698	0.485	– 0.001 to 0.002
Trial number|Visual condition (B_2) No FB vs FV	0.003	0.001	4.025	0.000	0.001 to 0.004
Subject	0.001	0.002			

Model: *Step Error* = B_0**Trial Number* + B_1**Visual Condition* + B_2*(*Trial Number*|*Visual Condition*)

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 (Fig. 3). However, they also increased their reliance on feedback visual information with practice (Fig. 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 was 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. 2020a, b) 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, and were 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. If this is the case, the change in feedback visual reliance may be interpreted as participants improved at the task they practiced a lot (full vision target stepping) and did not improve at the task they only practiced a little (target stepping without feedback visual information). 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 control 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. Finally, embedding the probes would allow for more equal distribution of limited and full vision practice, helping to balance any effects which may have been driven by locomotor learning.

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.

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Data availability Processed data and code are available at https://osf.io/vx7zd/. Raw data files are available upon request due to the size of the files.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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