Influence of Visual Augmented Feedback on Walking Speed Perception in Immersive Virtual Reality

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Abstract

In virtual reality (VR), established perception–action relationships break down because of conflicting and ambiguous sensorimotor inputs, inducing walking velocity underestimations. Here, we explore the effects of realigning perceptual sensory experiences with physical movements via augmented feedback on the estimation of virtual speed. We hypothesized that providing feedback about speed would lead to concurrent perceptual improvements and that these alterations would persist once the speedometer was removed. Ten young adults used immersive VR to view a virtual hallway translating at a series of fixed speeds. Participants were tasked with matching their walking speed on a self-paced treadmill to the optic flow in the environment. Information regarding walking speed accuracy was provided during augmented feedback trials via a real-time speedometer. We measured resulting walking velocity errors, as well as kinematic gait parameters. We found that the concordance between the virtual environment and gait speeds was higher when augmented feedback was provided during the trial. Furthermore, we observed retention effects beyond the intervention period via demonstrated smaller errors in speed perception accuracy and stronger concordance between perceived and actual speeds. Together, these results highlight a potential role for augmented feedback in guiding gait strategies that deviate away from predefined internal models of locomotion.

1 Introduction

Locomotion is coordinated by using sensory feedback from the visual, vestibular, and somatosensory channels integrated within cortical sensorimotor networks (Lau et al., 2014). By dynamically mapping a relationship that correlates feedback between sensory systems, humans establish a perception of themselves within the environment in order to ambulate through it (Lackner & DiZio, 1988; Mergner & Rosemeier, 1998; Frost et al., 2015; Gandevia et al., 1992). The relative translation of an individual's environment and the dynamic depth cues that it provides create a perception of self-motion concordant with the efferent commands, which helps interpret and modulate walking velocity (Prokop et al., 1997; Takamuku & Gomi, 2021). During overground walking, body-based cues complement optic flow driven visual information to determine heading direction and velocity (Warren et al., 2001). These

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linkages are context-dependent, meaning that mismatches between visual and somatosensory input can result in temporary bodily reinterpretations of limb dimensions and/or external forces (Lackner & DiZio, 1988; Mergner & Rosemeier, 1998). The mismatch of static and mobile sensory cues provided during treadmill walking results in a conflict among the systems that disrupts sensorimotor integration models (Wright, 2014; Hirjaková et al., 2020) and in turn alters both kinematic (Konczak, 1994; Lamontagne et al., 2007) and kinetic (Blonien et al., 2006) gait parameters. Thus, treadmill rehabilitation remains limited in cultivating skills that translate to overground walking tasks (Hollman et al., 2016) because of the mismatched environmental context. It is therefore critical to understand ways to reduce sensory conflict in order to increase the effectiveness of treadmill training.

During treadmill walking, static optic flow information and reduced vestibular signals from a lack of actual forward motion provide misinformation that the body remains stationary. Although vestibular interventions, such as galvanic stimulation, could reduce the conflict, we chose to intervene in the visual system because it is known to play a larger role in the perception of self-motion. Immersive virtual reality (VR) enables more precise visual field manipulation to attenuate static visual effects (Gallagher et al., 2020; Wright, 2014). However, processing optic flow via head-mounted displays (HMDs) induces adaptations in key gait parameters including wider, shorter, and more variable strides (Osaba et al., 2020). When walking overground, adaptations to virtual reality diminished with prolonged exposure, but retained a steady-state bias in values (Martelli et al., 2019). Through observing these changes in gait strategy, it is clear that the brain derives movement from visual information differently when provided by physical or virtual environments (Horsak et al., 2021; Besharat et al., 2022). What remains unclear are the effects of psychological and sensory factors driving the differing self-motion interpretations in a virtual space.

An inability to correctly interpret translational velocity from virtual visual cues may be responsible for promoting gait adaptations between contexts (Janeh et al., 2017). While immersed in virtual spaces, individuals may not isometrically map the optic flow velocity of the visual field to their selected locomotive speed (Durgin et al., 2005). An isometric mapping between the user's movement and the visual information provided by the scene would indicate a fixed one-to-one relationship, meaning that the user adopted a gait speed similar in magnitude to the translational velocity of the scene. However, virtual scenes are misinterpreted as moving slower than the actual value, with errors in estimation propagating as the speeds increase (Banton et al., 2005; Caramenti et al., 2018). Portions of this discrepancy have been attributed to the insufficient visual information available in the HMDs restricted field of view (FOV) (Steinicke et al., 2011) but key perceptual inconsistencies have persisted even as modern VR technologies continue to improve FOV and refresh rates.

Previous groups have successfully identified techniques to facilitate motion perception accuracy by manipulating the direction of gaze to increase peripheral optic flow within a limited environment (Banton et al., 2005). Others have taken a perception-driven approach and implemented user-selected translational gains to minimize feelings of sensory mismatch while walking (Kassler et al., 2010; Perrin et al., 2019). Despite the significant advancements made by these experiments, our understanding of how internal models of walking speed are calibrated by the virtual presentation of isometric optic flow still remains limited. Although non-isometric mapping of virtual speeds may induce a seemingly "natural" relationship between visual and body-based sensory cues, translational gains have been shown to elicit changes in gait that deviate further from overground walking (Janeh et al., 2017). A change in kinematic characteristics between similar perceived speeds suggests an apparent disconnect between the psychological representation of walking speed and biomechanical output in virtual spaces.

In virtual environments, inherent visual information may not necessarily reflect preconceived notions of scaling or realism, which may require the perceptual systems to adjust (i.e., recalibrate) internal representations and accommodate for this distorted perspective (Wright et al., 2014). Augmented feedback provides additional contextual information that would otherwise be unavailable to the individual from intrinsic sensory systems alone to facilitate changes in motor behavior (Winstein et al., 1996; Ranganathan & Newell, 2009). Through these motor learning paradigms, explicit feedback can improve the accuracy of internal model recalibration by aligning motion in a manner that reduces perceptual errors. Furthermore, there is evidence to suggest that sensorimotor adaptations induced in virtual environments may have aftereffects that carryover into both subsequent immersion and in the real-world (Wright, 2014). To our knowledge, augmented visual feedback has been incorporated into VR treadmill regimens in order to manipulate gait characteristics (Maestas et al., 2018) and motivational factors (Alhirsan et al., 2021), but prior studies have yet to characterize the impact on walking velocity perception.

In this study, we aim to explore whether incorporating augmented feedback into a virtual environment can promote congruence between perceived optic flow speed and self-selected walking speed. Lastly, we aim to categorize the effect of feedback driven recalibration on speed perception accuracy in subsequent trials once the referential stimulus is no longer available. We hypothesized that individuals: (1) would more closely achieve isometric mapping, (i.e., motor outputs for walking velocity will match optic flow input velocity) when augmented feedback is incorporated into the HMD virtual environment, (2) would not change step width when presented with augmented feedback, and (3) would retain the more accurate perception of optic flow in the next trial after augmented feedback was removed.

2 Methods

2.1 Participants

Ten young adults (2 females and 8 males; age: 26.06 ± 6.02 years) participated in this study. Individuals with self-reported prior occurrence of visually induced motion sickness were excluded from this study. Participants were asked to verbally report any conditions that may have impacted their ability to participate in this study before beginning the experiment, including instances of musculoskeltal, neurological, and or cardiac disorders. No adverse effects of VR use (i.e., dizziness, unsteadiness, or light-headedness) were reported during this experiment. To monitor participant discomfort during the trials, explicit instructions were given to participants to inform the researcher immediately if they felt unsafe or experienced any simulator sickness symptoms during the experiment. Before beginning the study, participants provided informed written consent in accordance with the Temple University Institutional Review Board approved protocol 28448.

2.2 Experimental Protocol

Each participant performed two blocks of experimental conditions presented in a randomized counterbalanced order during a single-day session. The two experimental conditions involved treadmill speed-matching with virtual visual optic flow either with or without augmented feedback described in more detail below. Prior to the experimental conditions, each participant familiarized themselves with how to walk on an SPT, by spending a 5-minute acclimation period on the treadmill. During the acclimation period, participants were first instructed to increase their walking speed until reaching a comfortable pace. Once the experimenter determined that the participant's self-selected speed was within the experimental range required to successfully complete the trials, participants were then asked to practice speeding up within their maximum range and slowing down to a complete stop for the remainder of the training session. After the 5-minute acclimation period concluded, participants verbally confirmed that they felt capable of achieving desired walking speeds on the SPT, and were ready to begin the remaining tasks.

During both experimental blocks, participants were presented with a series of optic flow speeds in the hallway VE in a randomized order. Optic flow speeds were normalized to a set of evenly spaced Froude values ($\mathrm{Fr} = 0.06 - 0.18$) evaluated as a function of participant leg length (l): $Fr = \frac{v^2}{lg}$, in which g is the gravitational constant on Earth at sea level (9.81 m/s) and v is the

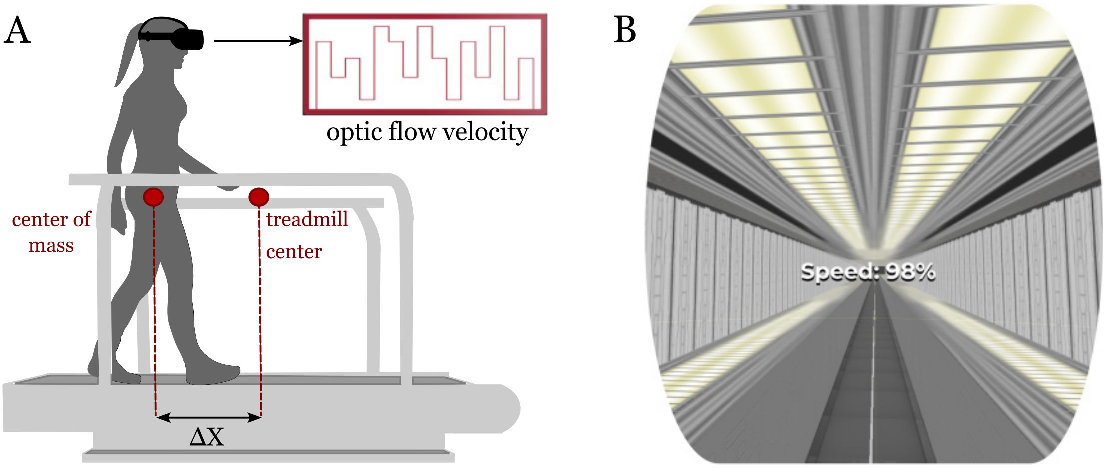

Figure 1. *The experimental paradigm incorporates a self-paced treadmill (SPT) with a novel head-mounted display (HMD) environment (A) A proportional–derivative (PD) control algorithm directs the treadmill motors to minimize displacement of the participant relative to the center of the treadmill (ΔX) using pelvic motion capture markers. (B) The virtual hallway environment is viewed using an HMD in each trial condition. Depicted is the continuous augmented feedback presented to the participant regarding speed-matching performance as a percentage value.*

translational velocity of the VE scene (Alexander, 1977). Speed changes occurred in a single frame and persisted for 1-minute intervals. A single trial consisted of three randomized blocks of five optic flow speeds, presented in succession for a total of fifteen minutes of walking. Participants were naive to both the number and frequency of speed changes within the session.

In the conditions containing no augmented feedback, participants were instructed to walk at a pace that best matched their perceived motion in the hallway virtual environment (VE) using all available visual cues. Participants did not receive any information during the trial regarding either how long they had been walking on the treadmill, or how accurately they were performing the task. Augmented feedback trials maintained a similar objective; however, participants were given additional instructions on a virtual speedometer and attempt to achieve 100% accuracy (see details in Methods Section 2.3, VR-Treadmill System) for the duration of the session. The trials ended once the hallway scene ceased motion, and the participants were instructed to slow down to a stop on the treadmill. A rest period was implemented between each block during which participants exited the virtual space.

2.3 VR-Treadmill System

Participants performed walking tasks on an instrumented treadmill (Bertec, Ohio, USA) operating in a self-paced (SPT) mode (see Figure 1A). A 16-camera motion capture system (sample rate: 120 Hz; Qualisys, Gothenburg, Sweden) tracked participant movement on the treadmill using a set of 39 reflective markers placed on relevant anatomical landmarks (34 lower body, 5 upper body). Motion capture data for the anterior-posterior location of four of these markers denoting the pelvis (bilateral anterior and posterior superior iliac spine) were averaged to estimate center of mass (COM) displacement along the belt. A proportional–derivative (PD) control algorithm drove SPT speed in real time using the following function of calculated COM values:

$$X'' = K_p \Delta X + K_d X' \tag{1}$$

$$V_T = V_0 + X'' \Delta t \tag{2}$$

where the position of the participant's COM relative to the center of the belt (ΔX) and the participant's current walking speed (X) determine the commanded acceleration value for adjusting the motor speeds (X'') (Minetti et al., 2003). Proportional and derivative gain values (K_p and K_d, respectively) were tuned to improve the response time of the system without introducing destabilizing oscillations. The measured body acceleration was added to the current treadmill velocity (V_0) multiplied by a desired rise time (Δt), to produce a new command to the treadmill (V_T). This self-pacing algorithm was implemented in Python 3.6 using the equipment's API.

An HMD device (Oculus Quest; Facebook Technologies, California, USA) with a refresh rate of 72 Hz displayed an immersive VE created with Unity game development platform (Unity Technologies, California, USA). The VE simulated an infinitely-repeating virtual hallway that expanded radially from a central point at a commanded target speed (Figure 1B). Transverse optic flow was presented using textured wall panels bilaterally bordering the participant's direction of motion and discretely scaled floor tiles representing the treadmill belt. Additional features were implemented to facilitate participant safety, including virtual reproductions of the treadmill handrails colocated in the VE with the actual handrail positions for spatial reference. However, participants were not permitted to use the physical treadmill handrails in order to limit conflicting tactile information provided during the trials unless faced with an immediate safety concern such as a loss of balance. Furthermore, a virtual boundary rendered warning signals for the participant if they approached the edges of the treadmill, super-imposing a view of the external environment if this boundary was exceeded.

During experimental conditions containing augmented feedback, speed-matching performance was presented to the participants as a visual element (Figure 1B). Self-selected gait speed as estimated by the aforementioned COM function was used to calculate the percent accuracy in reproducing congruent physical motion from the perceived visual speed (i.e., if the participant was moving faster than the speed of the HMD visual surrounding, a speedometer displayed a value above 100% and vice versa). The speedometer was located in the VE at a neutral head position for the participant's forward-facing line of sight in an earth-fixed reference frame. The speedometer element measured 0.75 m wide × 0.1 m tall in the virtual scene, taking up approximately 0.33% of the planar area of the hallway scene (7.5 m × 3.0 m). Concurrent speed-matching feedback was updated at the refresh rate of the HMD device, enabling participants to adjust their pace in accordance with the task. The communication network between the motion capture, treadmill, and VR systems was established through the robotic operating system (ROS) (Quigley et al., 2015).

2.4 Data Analysis

Kinematic data from calcaneus markers on both feet and the pelvis were used to identify heel strike gait events. Heel strikes were defined at the instance of maximal displacement between the pelvic estimated COM and heels marker during each cyclic gait phase (Zeni et al., 2008). Step length (SL) was computed from the difference in AP position of the bilateral calcaneus markers at heel strike in addition to a kinematic correction for treadmill walking as previously described by the authors (Canete & Jacobs, 2021). Briefly, this method incorporates the velocity of the treadmill belt through an estimation of the distance traveled during the push-off phase of motion. Walking velocity values were calculated as the SL over step time (ST) at each interval. Step width (SW) was calculated as the mediolateral (ML) distance between calcaneus markers at heel strike. Gait variability measures were computed for SW as the mean and coefficient of variation (CV) over the final sixty steps in each speed iteration in order to mitigate potential acceleration effects during speed changes.

2.5 Statistics

We verified that all walking velocity data was normally distributed across all conditions using the Anderson-Darling test. To test our first hypothesis, we examined the interaction of feedback type and optic flow speed (Froude Number) on velocity estimation error using a two-factor repeated measures analysis of variance (ANOVA). Our second hypothesis was addressed using a two-factor repeated measures ANOVA with similar fixed and random effects for each of the kinematic parameters (step width mean, step width CV). A similar approach was taken to address our final hypothesis regarding the retention effects of virtual feedback. A three-factor repeated measures ANOVA was performed to evaluate the main and interaction effects of feedback type, optic flow velocity, and presentation order on walking velocity responses. The relationship between virtual optic flow speed and walking velocity response was evaluated for each trial condition using a Pearson correlation coefficient and linear regression model. Statistical tests were performed in JMP Pro 16 (SAS Institute Inc., North Carolina, USA). All statistical tests set significance level at $p < .05$.

3 Results

3.1 Actual vs. Perceived Virtual Optic Flow Speeds

A two-factor repeated measures ANOVA (2 Feedback Conditions × 5 Optic Flow Velocities) demonstrated a significant main effect of optic flow velocity on self-selected walking velocity [$F(1{,}9) = 137.08$, $p < .001$]. There was not a main effect between with and without augmented feedback conditions [$F(1{,}9) = 3.48$, $p = .095$]; however, a significant interaction effect was observed between feedback type and optic flow speed [$F(1{,}9) = 16.76$, $p = 0.003$]. This interaction indicates that the presentation of visual feedback affects the relationship between input optic flow velocity and resulting walking velocity output as depicted in Figure 2. There was not a significant random effect observed for the participant ($p = 0.784$) on walking velocity.

For trials without augmented feedback, there was not a significant correlation observed between optic flow speed and self-selected walking velocity [$r(48) = .24$, $p = .087$]. However, in trials with augmented feedback, a significant positive correlation was observed between optic flow speed and self-selected walking speed [$r(48) = .88$, $p < .001$]. This was further demonstrated with a simple linear regression model, which showed a positive relationship between walking velocity and optic flow velocity [$m = 0.75$, $p < .001$, $b = 0.02$, $p = .006$]. Together, these results suggest that participants are likely to achieve a relationship between visual perception and walking speed that more closely approaches the 1:1 isometric ratio when augmented feedback is incorporated into the virtual environment.

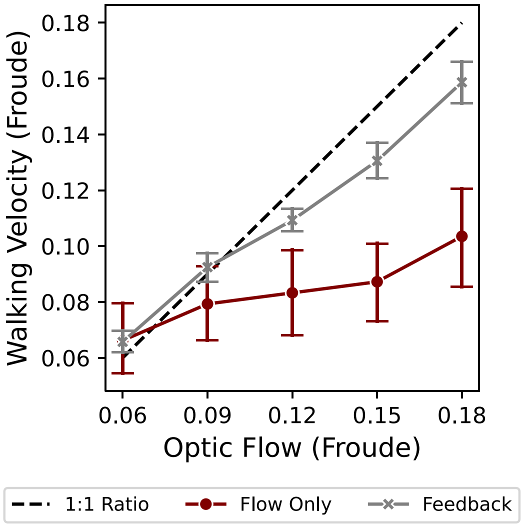

Figure 2. *Measured walking velocity responses are influenced by the presence of visual augmented feedback for optic flow speeds (N = 10). Each data point represents the mean walking speed across participants selected to match the optic flow velocity for one of two trials: without feedback (red) or with projected speedometer feedback (grey). Error bars indicate the standard deviation at each optic flow velocity. The dashed line represents the unity line, at which a 1:1 isometric ratio is achieved between optic flow and walking velocity.*

3.2 Step Parameter Modulations by Virtual Feedback Augmentation

To characterize cautious gait patterns we evaluated a two-factor repeated measures ANOVA (2 Feedback Conditions × 5 Optic Flow Velocities) for the speed-independent base of support measures (SW mean and CV) demonstrated in Figure 3. This analysis revealed no significant effects of feedback condition [$F(1{,}9) = 1.44$, $p = .261$], optic flow velocity [$F(1{,}9) = 0.20$, $p = .667$], or their interaction [$F(1{,}9) = 0.001$, $p = .971$] on mean step width (SW). However, a significant random effect was observed for the participant ($p = .037$).

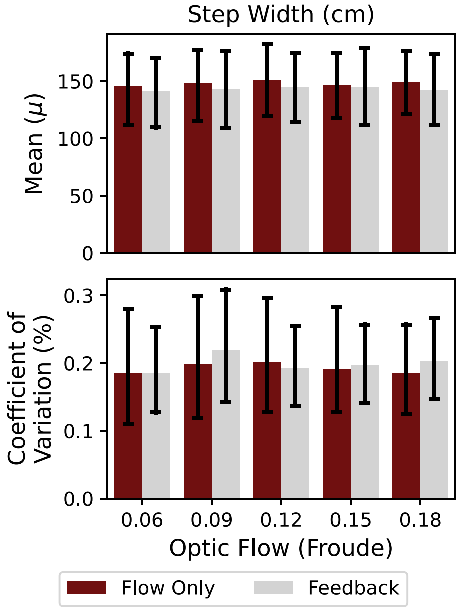

Figure 3. *Step width means (μ) and variability (coefficient of variation) are not impacted by the presence of visual augmented feedback (N = 10). Data is shown for each of the five evenly-spaced virtual optic flow speeds: 0.06–0.18. Error bars represent the standard deviation at each optic flow velocity. In both feedback conditions (flow only, feedback), participants adopted a similar average step width with step width variation across all five speeds that varied by individual.*

Similarly, no significant effects were observed on SW coefficient of variation from feedback condition $[F(1,9) = 0.21, p = .657]$, optic flow velocity $[F(1,9) = 0.005, p = 0.947]$, or the interaction $[F(1,9) = 0.27, p = .618]$. A significant random effect was observed for the participant ($p = .042$). These findings suggest that participants adopted consistent parameter values for SW and SW variability that differed between individuals, but remained consistent across optic flow speeds regardless of whether feedback was incorporated into the VE.

3.3 Retention Effects of Feedback Augmentation on Self-Motion Perception

A three-factor repeated measures ANOVA (2 Feedback Conditions × 2 Presentation Order Conditions × 5 Optic Flow Velocities) was conducted to assess the potential retention effects of augmented feedback on self-motion perception. In addition to reaffirming the significant effects demonstrated in the previous two-factor repeated measures ANOVA analysis, an interaction effect was observed between feedback type, trial order, and optic flow speed $[F(1,8) = 5.98, p = .040]$. This three-way interaction suggests that the exposure order of the conditions, in combination with the presence of augmented feedback itself, may impact the relationship between visual information and walking velocity demonstrated in Figure 4.

Walking velocity was positively associated with optic flow velocity in both trials containing augmented (i.e., speedometer) feedback regardless of the order in which they were presented (Augmented Feedback First: $r(23) = .84, p < .001, m = 0.69, p < .001, b = 0.03, p = .037$; No Augmented Feedback First: $r(23) = 0.92, p < .001, m = 0.80, p < .001, b = 0.02, p = .082$). In trials without augmented feedback that presented only optic flow, no correlation was observed between optic flow velocity and walking velocity if this was the first task conducted by the participant ($r(23) = .08, p = .701$). However, if participants had preceding exposure to augmented feedback, they retained a positive association between optic flow velocity and walking velocity once the augmented feedback was removed from the virtual scene ($r(23) = 0.48, p = .017, m = 0.45, p = .017, b = 0.03, p = .167$).

4 Discussion

Optic flow simulated in a virtual environment has been shown to induce underestimations of walking speed when reproduced in the physical world (Banton et al., 2005). Differences between this perceived and realized velocity create discordance between one's internal model of locomotor speed and one's actual speed which can induce kinematic gait changes while walking in virtual spaces. This study investigated the impacts of augmented visual feedback on promoting isometric self-motion perception in a virtual environment. Additionally, we characterized kinematic gait modulations

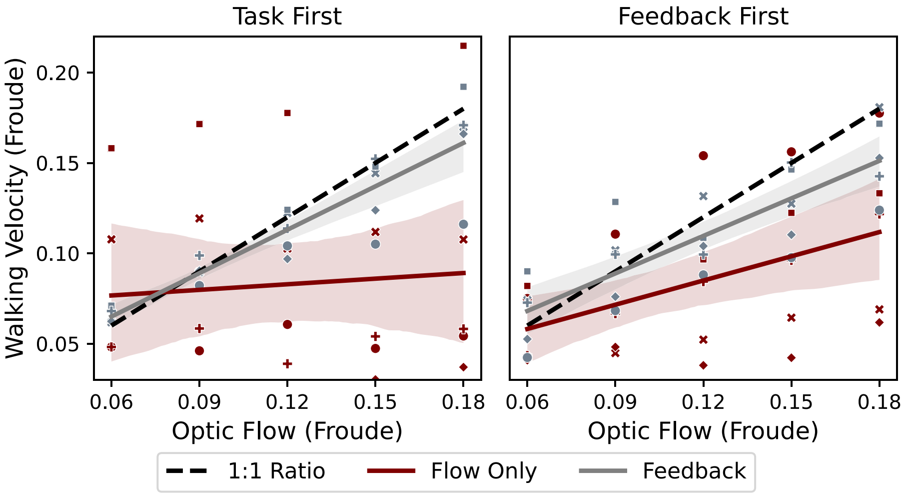

Figure 4. *Feedback presentation order is linked to self-motion perception from optic flow speeds between conditions. Each subplot reflects the order in which the identical experiments (Flow Only, Feedback) were conducted: Task First (N = 5) and Feedback First (N = 5). Each marker type represents the performance of a single participant for each of the two experiments. Red (Flow Only) and Grey (Feedback) lines represent the estimated linear regression model and 95% confidence intervals for each experimental condition. Dashed lines represent the unity relationship, at which a 1:1 isometric ratio is achieved between optic flow and walking velocity.*

and performance carryover between subsequent bouts of walking to identify perception-action recalibration effects from velocity feedback.

Our results highlighted a significant interaction effect between the presence of augmented feedback and optic flow velocity that altered the corresponding relationship with self-selected walking speed. When participants were tasked with interpreting velocity solely using visual flow information (e.g., texture gradient resolution, increasing retinal image size, binocular convergence, and accommodation effects), the degree of self-motion underestimation intensified for increased optic flow speeds, reaffirming the findings of previous groups (Banton et al., 2005; Perrin et al., 2019).

Differences in average walking velocities were only observed between optic flow extremes, demonstrating that in general, participants maintained a relatively constant velocity for the duration of the trial. A lack of correlation between sensory observations in the virtual space and motor output suggests that participants may be unable to recover translational velocity information from optic flow alone at higher speeds without supplementary cues. One potential explanation for this finding highlights the optimization trade-off between feedforward gait control using CPGs and sensorimotor feedback integration that occurs during typical overground walking (Frigon et al., 2021; Ryu & Kuo, 2021). Gait control becomes increasingly autonomic at higher velocities as rhythmic motor patterns dominate motor planning over peripheral sensory information (Harischandra et al., 2011; Brandt et al., 1999). At faster optic flow speeds, participants may therefore exhibit difficulty aligning motor output with a strictly visual platform such as virtual reality without recalibration of internal perception–action models.

In support of our first hypothesis, a significant linear correlation was observed between optic flow velocity and self-selected walking speed when augmented feedback was incorporated into the virtual space. Cognitive processing of walking accuracy through continuous augmented visual feedback enabled participants to more accurately reproduce an isometric walking speed within the virtual space, mitigating optic flow underestimation. Recovery of walking velocity congruence indicates that augmented feedback information can be incorporated into perceptions of self-motion that deviate from habitual sensory models of optic flow. It is well established that internal spatial models can be dynamically updated as individuals recalibrate motor plans to accommodate decoupled perceptual experiences (Rieser et al., 1995; Mohler et al., 2007; Kelly et al., 2014). Our use of walking accuracy feedback to drive speed adaptations in a VE suggests a further role for cognition in re-learning the relationship between self-motion perception and locomotion (Maestas et al., 2018).

Kinematic variables trend toward a cautious gait pattern when locomoting in virtual spaces, potentially as a response to perceived risk of falling (Horsak et al., 2021). Notably, individuals have been shown to adopt a slower pace, wider step width, and increased step width variability when walking while wearing an HMD. To determine if the observed decreases in walking speed between feedback conditions were simply an indicator of participant discomfort with the task rather than a recalibration of internal spatial models, we characterized supplemental velocity-independent measures of conservative gait. Across optic flow speeds, participants adopted an individualized value for both mean step width and step width CV that remained constant regardless of the feedback condition. Previous groups have demonstrated that the complexity of a directed focus task as well as the nature of the instructions can have additional implications on dynamic stability measures (Mak et al., 2018; Kelly et al., 2010). Furthermore, in virtual environments, the perceptual load of a task has been shown to impact self-selected walking velocities dependent on the ecological density of the optic flow information provided in the scene (Ludwig et al., 2018). A lack of an observed effect for feedback condition on either kinematic parameter indicates that the differing focus demands of the speedometer task did not significantly alleviate other indicators of cautious gait in VR. Our results suggest instead that the faster and more accurate gait speeds associated with augmented feedback could be due to calibration of the optic flow with sensorimotor processing which helped fine-tune the internal perception–action model for walking in a virtual environment.

Our results demonstrate a significant interaction effect between feedback type, optic flow velocity, and presentation order of the speedometer stimulus on speed-matching accuracy. Re-learned internal modeling relationships for spatial representations have been observed to carry over into subsequent motor behaviors once the sensory calibration stimulus is removed (Weiss et al., 2014; Wright, 2013). When tasked with guiding locomotion without augmented feedback, participants performed better if they had previous exposure to feedback training, as demonstrated by the recovery of a significant correlation between optic flow and walking speed. Although there is a reduced peripheral optic flow density in a VE compared to a traditional environment (Steinicke et al., 2011), these results suggest that there are still sufficient visual cues to drive self-motion perception after recalibration in the augmented feedback condition. Taken together with other findings using virtual reality which have shown that important parameters of the virtual space include the contrast ratio (Stone & Thompson, 1992), field of view (Caramenti et al., 2019), and focal direction (Banton et al., 2005), these results highlight sensorimotor calibration as a further consideration factor for aligning isometric speed perception during VR immersion.

Although the findings of this study provide insight into the recalibration process for recovering translational self-motion in virtual environments, we acknowledge that they are not without limitations. Primarily, the small sample size for each group in our three-factor ANOVA analysis for presentation order is a limiting factor. In addition, eye-tracking was not available in our hardware platform to track shifts in attentional focus between tasks. Therefore, we cannot measure the time spent fixating on the speedometer itself to disentangle the potential impacts of attentional changes between tasks on walking speed. Furthermore, we cannot fully discount potential timing effects from prolonged exposure to the virtual scene. We aimed to mitigate this impact through an initial adaptation period before beginning the trials; however, a learning effect may be present as participants adapt to the task at hand. The possibility of a ceiling effect for performance in the trials containing augmented feedback may obscure a timing effect in our findings.

Future studies should aim to disentangle the impacts of training exposure from recalibration effects by including a counterbalanced condition without the inclusion of feedback in either testing session.

5 Conclusion

In summary, our results show that participants are capable of adopting walking velocities that deviate away from the optic-flow underestimations typically observed in virtual spaces by applying augmented task-specific feedback. Participants consistently misperceived the speed of visual flow in the virtual HMD-VR scene without augmented feedback while walking on an SPT, but recovered an ability to accurately reproduce virtual speeds when incorporating speedometer feedback into their motor plans. A reduction in walking velocity for the HMD optic-flow simulation was not accompanied by speed-independent cautious gait characteristics indicative of decreased dynamic stability. Furthermore, we have shown that locomotion perception–action coupling can be relearned with augmented visual feedback and retained and transferred to subsequent optic flow speed interpretation tasks. These findings suggest that both visual optic flow cues and visuomotor calibration contribute to an individual's perception of isometric translational motion in VR environments.

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