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## A role for the lower visual field information in stair climbing

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### ABSTRACT

**Background:** Locomotion on stairs is challenging for balance control and relates to a significant number of injurious falls. The visual system provides relevant information to guide stair locomotion and there is evidence that peripheral vision is potentially important.

**Research question:** This study investigated the role of the lower visual field information for the control of stair walking. It was hypothesized that restriction in the lower visual field (LVF) would significantly impact gaze and locomotor behaviour specifically during descent and during transition phases emphasizing the importance of the LVF information during online control.

**Methods:** Healthy young adults ( $n = 12$ ) ascended and descended a 7-step staircase while wearing customized goggles that restricted the LVF. Three visual conditions were tested: full field of view (FULL); 30° (MILD), and 15° (SEVERE) of lower field of view available. Stride time, head pitch angle and handrail use were assessed during approach, transition steps (two steps at the top and bottom of the stairs) and middle step phases.

**Results:** Transient downward head pitch angle increased with LVF restriction, while walk speed decreased and handrail use increased. Occlusion impaired stair descent more strongly than ascent reflected by a larger downward head pitch angles and slower walk times. LVF restriction had a greater influence on stride time and head angle during the approach and first transition compared to other stair regions.

**Significance:** Information from the lower visual field is important to guide stair walking and particularly when negotiating the first few steps of a staircase. Restriction in the lower visual field during stair walking results in more cautious locomotor behaviour such as walking slower and using the handrails. In daily activities, tasks or conditions that restrict or alter the lower visual field information may elevate the risk for missteps and falls.

### 1. Introduction

Vision provides crucial information to guide movement, with peripheral vision being especially important for locomotion. Visual input from the lower visual field (LVF) guides stepping reactions in response to balance perturbations [1], and gait adjustments to avoid obstacles [2]. In individuals with simulated and acquired visual field loss, impairment in the central 21° of the visual field, or in the LVF up to a 58° radius, is associated with reduced gait speed and increased rate of collisions with objects during locomotion [3–5]. Thus, visual information from the LVF allows the central nervous system to control and adapt locomotion without the need for initial redirection of gaze towards obstacles or the landing area.

While the role of peripheral vision has been investigated during level ground walking, our previous work on gaze behaviour also provides indirect evidence for the contributions of peripheral vision in stair locomotion [6–8]. Specifically, we showed that central visual

information about the stairs is unlikely a requirement for stair ascent/descent, since individuals can successfully climb stairs with minimal gaze deviations and foveal fixations towards the stairs [7,8]. Accordingly, a recent study showed that, when the LVF is unavailable during stair ascent, foot clearance increases in the first steps, supporting the role of peripheral vision guiding online foot placement [9]. However, the role of the LVF in stair locomotion has been demonstrated only indirectly by the lack of foveal gaze behaviour directed to the stairs, or under a fixed restriction in the LVF, thus the extent of the LVF required to guide stair locomotion and associated gait adjustments are unclear.

The present study sought to advance understanding of the role of peripheral vision in stair walking by systematically varying the level of restriction in the LVF. We hypothesized that a severe restriction in the LVF would lead to two behavioural consequences. First, we predicted changes in gaze behaviour revealed by a change in head angle (to redirect gaze). Second, we expected a conservative locomotor behaviour marked by a reduction in walking speed and increased handrail use.

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Additionally, we also expected that the dependence on the LVF information would be differentially influenced by direction (ascent versus descent) and location on stairs (transition versus mid stairs). Since the view of the stairs is further in the peripheral vision during stair descent, we expected that locomotor behaviour would be more affected by the visual occlusion during descent compared to ascent, observed by increased handrail use, reduction in gait speed, and increase in head angle. We also expected that a severe restriction in the LVF would have a stronger effect during the transition to stairs, demonstrated by increased head angle, reduction in gait speed, and use of handrails during the approach to the stairs and during the transition.

**2. Methods**

**2.1. Participants**

Twelve healthy young adults ( $29.7 \pm 3.1$  years; 6 females) participated in this study. Participants were free of medical conditions affecting their balance or ability to climb stairs and showed normal or corrected to normal visual acuity. This study was approved by the Office of Research Ethics at the University of Waterloo, and all participants provided written informed consent.

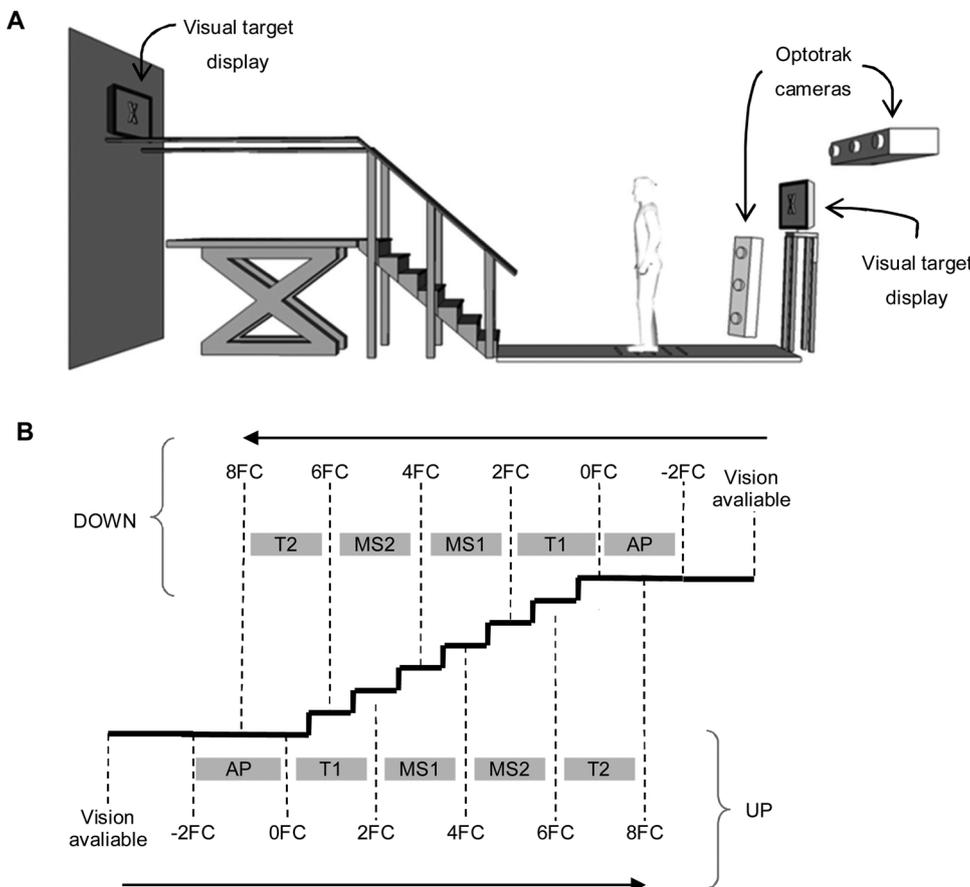
**2.2. Protocol**

Participants walked up and down a 7-step staircase (96 cm wide, 18 cm rises, 26 cm treads, handrails on both sides; Fig. 1A). A 2.5-meter walkway was extended at each end of the stairs. Participants wore a safety harness attached to a retractable lanyard running along a cable above the stairs and walkway. At the beginning of each trial, participants were asked to look straight ahead while standing at one of 5 different start points marked on the floor. The start points were spaced

20 cm apart to prevent memorization of the distance from the stairs. Participants performed at least 3 steps before and after the stairs. Participants alternately ascended and descended the stairs at a self-selected pace.

Three visual conditions were tested: 1) *full visual field* (FULL); 2) *mild occlusion* (MILD): 30° of the LVF available, and 3) *severe occlusion* (SEVERE): 15° of the LVF available. Visual occlusion was made with a pair of safety goggles which lenses were covered with adhesive paper to create the desired level of occlusion. Occlusion level was individually determined with an arc perimeter: with the head supported in a forehead/chin-rest, the participant fixated on the central point in the arc perimeter and slowly moved a piece of cardboard covering the surface of the goggles until they were able to see a target respectively at 15° and 30° below the fixation point. The position of the cardboard was tested 3 times for each occlusion level and the average value was used to cover the goggle lenses during the experimental trials. During the FULL condition, participants wore the same pair safety goggles with unobstructed lenses.

To better reveal head pitch instances and prevent continuous downward head orientation, in half of the trials participants continually looked at a visual target at the end of the walkway during stair walking (FIX). The visual target consisted of a letter “X” displayed on a computer monitor (3 m from the stairs; 1.5 m height) at each end of the walkway (i.e., upstairs and downstairs). In the other half of the trials, participants received no specific instruction on where to look (FREE). Participant performed blocks of 5 trials in each condition combining stair direction (UP and DOWN), visual field (FULL, MILD, SEVERE), and gaze (FIX and FREE), totalling 60 trials. Blocks were randomly presented across subjects.



**Fig. 1.** (A) Schematic of the experimental setup (details in the text). (B) Classification scheme for participant's location when ascending (UP) and descending (DOWN) the stairs. Top and bottom of the figure shows location coding for stair descent and ascent, respectively. AP = approach; T1 = first transition; MS1 = first mid stair region; MS2 = second mid stair region; T2 = second transition; -2FC = two foot contacts before stepping on the stairs; 0FC = last foot contact before the stair; 2FC = foot contact on the step 2; 4FC = foot contact on the step 4; 6FC = foot contact on the step 6; 8FC = first foot contact out of the stairs.

### 2.3. Data acquisition and analysis

Step timing (foot contact and foot-off) were recorded with footswitch insoles (B&L Engineering, Tustin, USA). An infrared switch recorded the timing just prior to contact with the bottom step. Footswitch and infrared switch data were recorded at 240 Hz with a customized program (Labview, National Instruments, Austin, USA), and combined to determine participants' stepping location with respect to the stairs. Participant's location on the stairs was classified every 2 steps in the following categories (Fig. 1B): *approach* (AP), *first transition* (T1), *first mid steps* (MS1), *second mid steps* (MS2), and *second transition* (T2). Walk time was calculated for total stair walk (from 2 steps prior to 2 steps following the stairs), as well as for each stair region (AP, T1, MS1, MS2, T2). Handrail use was video recorded and calculated per condition.

Head movements were recorded with an Optotrak system (3020, Northern Digital, Waterloo, Canada). Clusters of active markers were placed at the forehead and back of the head and collected at 120 Hz. Head marker data were filtered at 2 Hz and used to calculate head pitch angle using a Cardan x-y-z rotation sequence. Head pitch angle was calculated about the mediolateral axis of the head coordinate system (positive to the left) and normalized by the head angle during quiet standing, with the participant looking comfortably straight ahead. Thus, a greater head angle denoted greater head pitch downward. The mean head angle and mean head angle variability (standard deviation) were calculated per participant and per condition.

Walk time, mean head angle, head angle variability, and handrail use were analyzed with 3-way repeated-measures ANOVAs with direction (UP vs. DOWN), visual occlusion (FULL, MILD, SEVERE), and visual target (FREE vs. FIX) as factors. Provided that these analyses showed a similar trend for all variables between FREE and FIX, walk time, mean head angle, and head angle variability in FREE were independently analysed by three-way ANOVAs with occlusion (FULL, MILD, SEVERE), stair direction (UP, DOWN), and stair region (AP, T1, M1, M2, and T2) as factors. FREE was selected as opposed to FIX because it provided a more ecologically relevant condition. Post-hoc analysis (Tukey adjustment) was performed to characterize differences across conditions and a significance level was set at 0.05 for all analyses.

## 3. Results

### 3.1. Head angle

For mean downward head angle, ANOVA evidenced significant main effects for direction ( $F(1,11) = 97.43$ ,  $p < 0.0001$ ), occlusion ( $F(2,22) = 25.78$ ,  $p < 0.0001$ ), and gaze ( $F(1,11) = 6.03$ ,  $p = 0.032$ ; Fig. 2A), and an interaction between direction and occlusion ( $F(2,22) = 3.93$ ,  $p < 0.035$ ; Fig. 2B). While downward head angles were greater in DOWN than in UP and increased with occlusion, the difference between MILD and SEVERE was only significant in DOWN

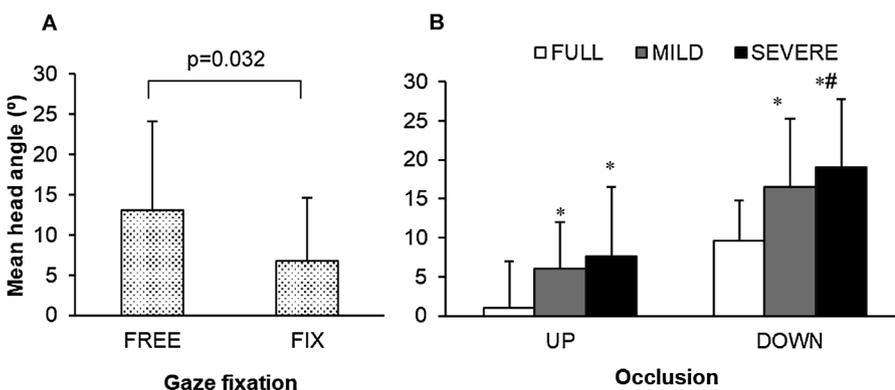


Fig. 2. A) Mean head angle as a function of gaze fixation. B) Mean head angle across walk direction and occlusion. (FULL: full vision, MILD: 30° LfV available; SEVERE: 15° LfV available; FREE: no visual target; FIX: visual target; UP: stair ascent; DOWN: stair descent; \*significant different from FV in the respective walk direction ( $p < 0.001$ ). #significant different from MILD in the respective walk direction ( $p < 0.05$ ).

( $p < 0.05$ ).

While the FIX condition produced smaller head angles than FREE, the interactions with direction of walking and occlusion were non-significant. As a result, we analysed head angle differences across stair regions only in the FREE condition (noting that head angles in FIX showed a similar trend). A three-way ANOVA evidenced significant main effects for direction ( $F(1,11) = 89.96$ ,  $p < 0.0001$ ), occlusion ( $F(2,22) = 20.54$ ,  $p < 0.0001$ ) and stair region ( $F(4,88) = 25.06$ ,  $p < 0.0001$ ), and significant stair direction vs. stair region ( $F(4,44) = 27.15$ ,  $p < 0.0001$ ), and occlusion vs. stair region ( $F(8,88) = 9.97$ ,  $p < 0.0001$ ) interactions. The direction vs. stair region interaction (Fig. 3A) indicated that mean head angle was greater in DOWN compared to UP in all stair regions excluding in T2. Also, head angle gradually decreased along all stair regions during DOWN, while decreasing only from AP to M1 within the UP condition. The occlusion vs. stair region interaction (Fig. 3B) indicated that, mean head angle remained relatively constant across stair regions with FULL vision, but both MILD and SEVERE occlusions resulted in significantly greater mean head angles across all stair regions excluding T2.

For head angle variability, there was a main effect for occlusion ( $F(2,22) = 12.87$ ,  $p < 0.001$ ), stair region ( $F(4,88) = 9.96$ ,  $p < 0.0001$ ), and an interaction for occlusion vs. stair region ( $F(4,44) = 4.97$ ,  $p < 0.0001$ ). The occlusion vs. stair region interaction indicated that head angle variability remained constant across all stair regions with FULL vision, but it was significantly greater at the approach and initial transition phases in SEVERE occlusion, and at the transition phase in the MILD occlusion (Fig. 3C).

### 3.2. Locomotion

For the overall stair walk time there was a significant main effect of occlusion ( $F(2,22) = 22.86$ ,  $p < 0.001$ ), and interaction between direction vs. occlusion ( $F(2,22) = 5.12$ ,  $p = 0.0149$ ; Fig. 4A). Walk time significantly increased with occlusion level, but differences between UP and DOWN were only significant in the full vision condition. The main effect of gaze (FREE vs. FIX) only reached marginal statistical significance for stair walk time ( $p = 0.0559$ ).

For stride time, there were significant main effects for direction ( $F(1,11) = 9.39$ ,  $p = 0.0108$ ), occlusion ( $F(2,22) = 12.62$ ,  $p < 0.001$ ) and stair region ( $F(4,44) = 14.74$ ,  $p < 0.0001$ ), and significant interactions between direction vs. stair region ( $F(4,44) = 61.64$ ,  $p < 0.0001$ ), and occlusion vs. stair region ( $F(8,88) = 4.84$ ,  $p < 0.0001$ ). The direction vs. stair region interaction (Fig. 4B) revealed that stride time was increased during the approach and first transition in DOWN, and in the last transition in UP. The occlusion vs. stair region interaction (Fig. 4C) revealed that SEVERE occlusion significantly increased stride time in T1 and T2 compared to FULL and MILD conditions.

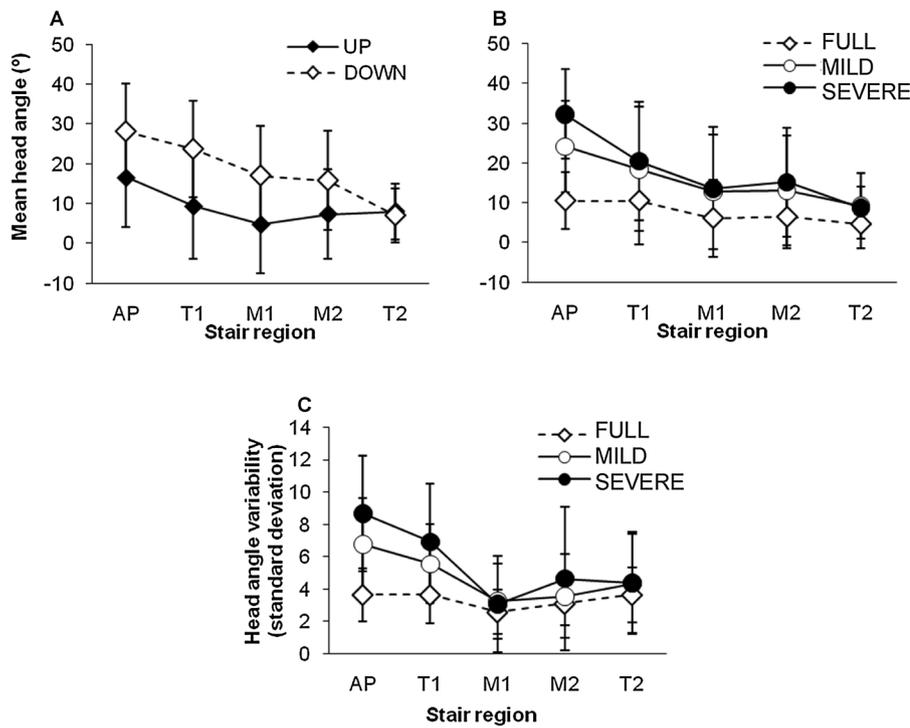


Fig. 3. Mean head angle in each stair region according to stair walking direction (A) and in the three levels of occlusion (B). Head angle variability in each occlusion level by stair region (C); FULL: full vision; MILD: 30° LFV available; SEVERE: 15° LFV available; FREE: no visual target; FIX: visual target; UP: stair ascent; DOWN: stair descent; AP: approach phase; T1: first transition; M1: mid steps 1; M2: mid steps 2; T2: second transition.

### 3.3. Handrail use

Handrail use significantly increased with both MILD and SEVERE occlusions ( $F(2,22) = 4.78, p = 0.019$ ; Table 1). Overall, occlusion in the LVF resulted in more participants holding the handrails and an

increase in the percentage of trials with handrail use.

### 3.4. Missteps and pauses in walking

No participant lost balance requiring the use of the harness to stop a

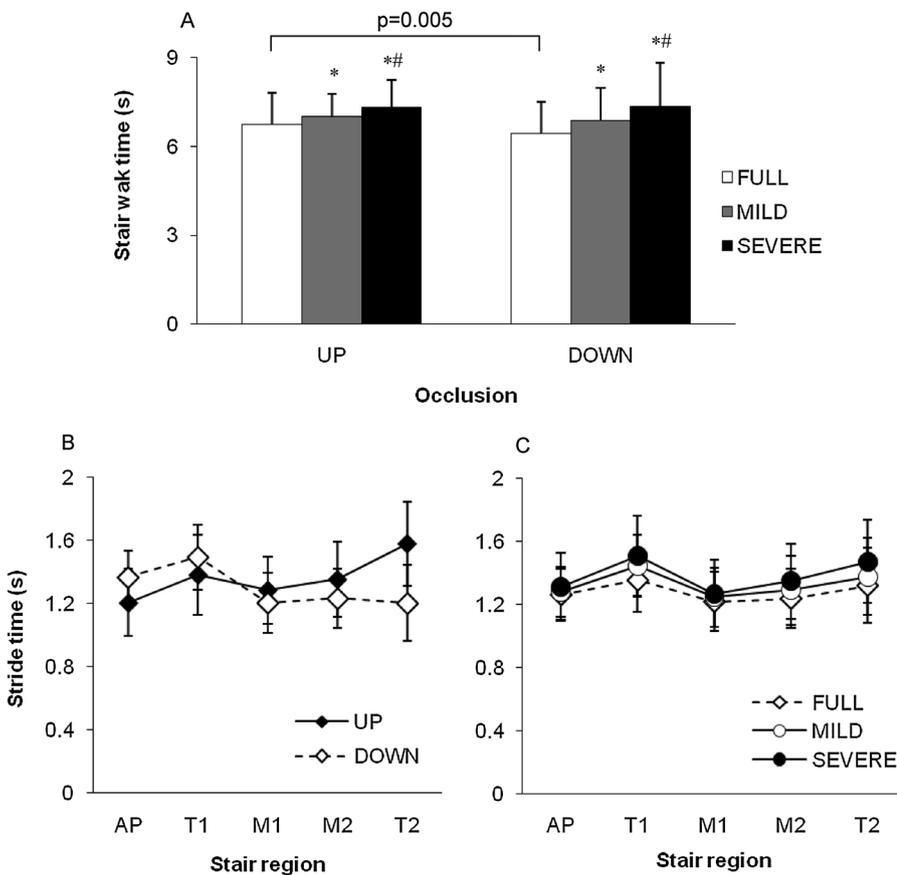


Fig. 4. A) Stair walk time across occlusion levels for UP and DOWN. B) Stride time in each stair region for UP and down. C) Stride time in each stair region according to occlusion. (FULL: full vision; MILD: 30° LFV available; SEVERE: 15° LFV available; \*significant difference with respect to full vision condition ( $p < 0.05$ ); #significant difference compared to respective MILD condition).

**Table 1**

Summary of handrail use. Total number of trials with handrail use and respective percentage of trials were calculated across all participants according to stair direction, occlusion level and gaze task. The number of participants who contacted the handrails for each condition is also shown.

	UP			DOWN		
	FULL	MILD	SEVERE	FULL	MILD	SEVERE
<b>FREE</b>						
Number of trials	19	28	29	18	27	39
Percentage of trials (%)	32.2	48.3	49.2	31.0	47.4	66.1
Number of participants	4	6	6	4	6	8
<b>FIX</b>						
Total number of trials	24	33	38	32	33	40
Percentage of trials	40.7	56.9	65.5	56.1	56.9	66.7
Number of participants	5	7	8	7	7	8

**Table 2**

Summary of observed events causing interruption of alternate gait pattern.

Direction	Occlusion	Gaze	Participant	Event
UP	SEVERE	FIX	S3	Expected an extra step at the bottom
	MILD	FREE	S2	Instability backwards at the first step
DOWN	FULL	FREE	S8	Missed the last step
		FIX	S10	Missed the last step
	MILD	FREE	S8	Missed the last step
		FIX	S10	Stopped walking prior to first step and reached for the handrail
	SEVERE	FREE	S11	Expected an extra step at the bottom
			S1	Expected an extra step at the bottom
			S6	Did not expect the last step (participant thought having reached the last step at step# 5-6)
		FIX	S3	Stopped walking prior to the first step to look down
			S7	Expected an extra step at the bottom

fall during this study. However, we observed in a few trials events which interrupted/alterd stair walking (Table 2). Most events occurred during stair descent and under some level of visual occlusion. In many trials, participants reported they were “expecting one more step”, and the foot landed on the ground as it was reaching the stairs. Video recordings from these trials indicate a clear disruption to walking and some degree of instability. However, there were also trials characterized by unusual foot contacts that did not result in apparent interruption of walking, most commonly during stair descent and seen as the heel making contact with the edge of the step during the swing phase. This heel contacts on the edge of the steps were observed in the video recordings and also confirmed by the footswitch data. From the observed 25 heel contacts on the step edge, 5 were in FULL, 5 trials in MILD and 15 trials in SEVERE. In all of these 25 trials, there was no apparent loss of balance or interruption of the alternate stair climbing pattern.

#### 4. Discussion

This work investigated the role of peripheral vision in stair locomotion and revealed that healthy young adults altered their stair walking behaviour when the LVF is restricted. Occlusion of the LVF resulted in increased head angle downward and decreased walk speed. It was also observed an increase in handrail use and unusual events when the LVF information was unavailable. Occlusion of the visual field was more disruptive during stair descent than in stair ascent, and during the approach to the first transition compared to other stair regions.

Our findings indicate a key role for visual information acquired from the LVF during stair locomotion. When the LVF was restricted,

individuals walked more cautiously on the stairs by reducing gait speed and using the handrails. Such cautious behaviour has been reported when peripheral vision is restricted in other locomotor tasks, such as walking over obstacles [10] and on irregular terrains [11], however our finding is inconsistent with previous work on stair ascent that found that gait speed did not change as a function of LVF occlusion [9]. A possible explanation for such difference in findings is that by adding different start points, we added more trial-to-trial uncertainty about stairs location which resulted in cautious walking and better revealed the contribution of peripheral vision for online control of stair locomotion.

The LVF occlusion had a stronger effect on stair descent than ascent, possibly because restriction in the LVF blocks a larger area containing the view of the stairs during stair descent, while during stair ascent, the view of the stairs (or at least some steps) is available in the upper visual field. The stronger dependency on visual information from the LVF during stair descent may relate to the increased challenge for stability and greater rate of accidents and injuries during stair descent compared to ascent [12,13].

In the present study, even a mild occlusion level (i.e., at least 30° of the LVF available) led to changes in head angle and locomotor behaviour, suggesting that a large LVF extent is necessary to guide stair walking. However, previous work reported that head tilts were not observed during stair ascent when peripheral vision was occluded [9]. Such inconsistency of findings is likely due to differences the testing protocol. First, our systematic approach to implement the LVF occlusion allowed varying the levels of restriction consistently between participants. Second, by varying the start positions before each trial, we increased the requirement for online visual control and reduced reliance on memory to guide stair walking. Finally, our findings from the FIX and FREE conditions also suggest that individuals naturally chose to orient their heads more downward when the LVF was restricted, and when that was not possible (FIX), they increase handrail use and alter their gait. Arguably, the capacity to see the stairs in the LVF in the present study could have been influenced by the subjects' height and variability in the visual occlusion ( $\pm 5^\circ$  between participants). However, the present findings evidenced that head pitch angles increased at a rate to approximately compensate the level of occlusion. Altogether, these findings further demonstrate the importance of the LVF in the online control of stair negotiation.

This study also revealed the importance of peripheral visual information to negotiate stair transitions. When the LVF was restricted, participants adopted a cautious strategy by walking slower in the transitions between stairs and level ground. This finding is in agreement with similar changes observed in other locomotor tasks [14,15], and the adoption of an alternate conservative strategy (increased foot clearance) during stair ascent [9]. During stair walking, the LVF provides information about the steps as well as about the near ground surface relative to the lower limbs. The increased magnitude and variability in head pitch during the approach and transition indicates the importance of the LVF information to negotiate the first steps in a staircase. Although speculative, the weaker effect of the LVF restriction on gait speed and head angle in the mid steps may indicate that the physical interaction with the first steps in a staircase provides sufficient information (e.g., proprioceptive information) about step geometry to reduce requirements for visual information when negotiating subsequent steps. Interestingly, restriction in the LVF had a smaller effect during the second transition (from stairs to level ground) in comparison to the first transition (from level ground to stairs). It is possible that some participants counted their steps on the stairs in this experiment of repeated trials. Of the 12 participants in the experiment, 3 participants actually declared they counted their steps every trial, while another three mentioned they counted sometimes and one participant admitted counting steps after a misstep (in the first block of trials). Anecdotally, counting steps is also a strategy used when individuals traverse stairs in the dark [16]. Additionally, a store spatial representation of the stair

could have been used to navigate the stairs in this study. Visual information can be retained for at least 4 strides (8 steps) to facilitate obstacle crossing, and for around 8 s to step on targets [17,18]. Thus, the short stair flight in the present study (7 steps), may have allowed the use of memory to control stepping throughout the entire staircase.

In summary, this study demonstrated the importance of the lower visual field information on stair walking and its particular importance when negotiating the first few steps in a staircase. Restriction in lower visual field information during stair walking results in more cautious locomotor behaviour such as walking slower and using the handrails. This work advances the understanding of the role of peripheral vision in the control of locomotor behaviour that has important implications in daily life activities. Our findings reinforce the potential risk of conditions or situations when the lower visual field is disrupted or occluded and provide fundamental knowledge to guide approaches to minimize occurrence of missteps and fall risk.

#### Conflict of interest statement

The authors have no conflict of interest to disclose.

#### CRedit authorship contribution statement

**Veronica Miyasike-daSilva:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Jonathan C. Singer:** Methodology, Software, Formal analysis, Data curation, Writing - review & editing. **William E. McIlroy:** Conceptualization, Methodology, Software, Formal analysis, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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