

Effects of Optic Flow Speed and Lateral Flow Asymmetry on Locomotion in Younger and Older Adults: A Virtual Reality Study

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The purpose of the study is to investigate whether there are age-related differences in locomotion due to changes in presence of vision, optic flow speed, and lateral flow asymmetry using virtual reality technology. Gait kinematics and heading direction were measured using a three-dimensional motion analysis system. Although older and younger adults were affected differentially by the availability of vision, a greater dependence on optic flow information in older adults during walking was not found. Linear relations were observed between walking performance and flow speed as well as heading direction and flow asymmetry. The findings suggest that the ability to integrate optic flow information into the multimodal system for assessment of walking speed and heading direction is comparable in older and younger adults.

Key Words: Optic flow speed—Virtual reality—Locomotion—Interlimb coordination—Heading direction—Visual dependence.

THE control of locomotion depends on the integration of information from visual, vestibular, and somatosensory systems. When information from one or more sensory systems is withdrawn or becomes less reliable, the central nervous system changes its weighting of sensory inputs to maintain appropriate postural responses (van der Kooij, Jacobs, Koopman, & van der Helm, 2001). A number of studies have reported that older adults are more dependent on the availability of vision for posture and gait than are younger adults. For example, older adults show greater sway with eyes closed during quiet standing (Choy, Brauer, & Nitz, 2003; Hay, Bard, Fleury, & Teasdale, 1996; Manchester, Woollacott, Zederbauer-Hylton, & Marin, 1989) and display diminished head stability with eyes closed during walking (Cromwell, Newton, & Forrest, 2001, 2002) compared with younger adults. A greater reliance on vision in older adults is considered a central sensory reweighting deficit (Teasdale, Stelmach, & Breunig, 1991) and/or age-related peripheral sensory loss in the vestibular and somatosensory systems. However, some studies (Anderson, Mulder, Nienhuis, & Hulstijn, 1998; Konczak, 1994; Schubert, Prokop, Brocke, & Berger, 2005) did not find significant differences in locomotion between younger and older adults due to changes in visual information, especially when optic flow parameters were involved. Additionally, research findings on age-related changes in perception of optic flow are equivocal. Billino, Bremmer, and Gegenfurtner (2008) and Atchley and Andersen (1998) found that perception of radial optic flow was not affected by age, whereas Warren, Blackwell, and Morris (1989) and Gilmore, Wenk, Naylor, and Stuve (1992) reported increased thresholds for heading detection and mo-

tion coherence, respectively, with age. Whether older adults are more dependent on optic flow information compared with younger adults during locomotion is still open to further investigation.

Optic flow patterns and their changes are used to assess speed and direction of self-motion (Gibson, 1958). Previous studies demonstrate that gait parameters are inadvertently modulated by manipulations of optic flow speed. When optic flow speed decreases, walking speed (Prokop, Schubert, & Berger, 1997; Schubert et al., 2005; Varraine, Bonnard, & Pailhous, 2002) and stride length (Prokop et al., 1997; Schubert et al., 2005) increase; decreasing optic flow speed shows opposite effects. The manipulation of lateral asymmetry of optic flow speed influences heading direction in honey bees (Srinivasan, Lehrer, Kirchner, & Zhang, 1991) and young adults (Duchon & Warren, 2002). Bees and young adults steered away from the faster moving wall with larger differences of optic flow speeds, resulting in more drift. The purpose of the present study is to examine whether there are age-related changes in gait patterns and heading direction as a function of the presence of vision (eyes open vs. blindfolded vs. virtual environment), optic flow speed, and lateral flow asymmetry.

In addition to walking speed and stride parameters, how limbs dynamically coordinate in response to changes in optic flow speed during locomotion remains to be determined. Wagenaar and colleagues have shown that shifts between patterns of interlimb coordination would occur when an appropriate control parameter is scaled (Donker, Beek, Wagenaar, & Mulder, 2001; Wagenaar & van Emmerik, 2000). For example, when walking speed (i.e., a control

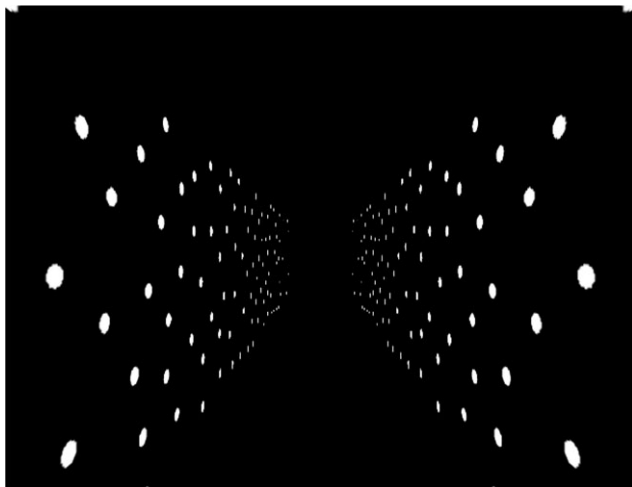


Figure 1. Display of virtual reality environment.

parameter) is systematically increased from 0.2 to 1.6 m/s, the arm-to-leg movement frequency ratio gradually changes from 2:1 (a less stable pattern) to 1:1 (a more stable pattern). The transition between coordination patterns is accompanied by an increased standard deviation of relative phase between arm and leg movements (Wagenaar & van Emmerik, 2000). Clinically, the degree of flexibility in interlimb coordination has been found to correlate with bradykinesia and rigidity in Parkinson's disease (Winogrodzka, Wagenaar, Booij, & Wolters, 2005) and with asymmetry in stroke (Ford, Wagenaar, & Newell, 2007). Older adults with risk for falls showed a reduced flexibility in their coordination of walking at speeds higher than 0.8 m/s compared with the walking patterns of healthy older adults (Wagenaar, Holt, Kubo, & Ho, 2003). The present study will investigate whether optic flow speed is an appropriate control parameter for changes in the coordination dynamics during walking and whether the coordination dynamics in response to changes in optic flow speed is age-related.

The first hypothesis is that older adults are more dependent on the presence of visual information during walking compared with younger adults, as shown by a reduced walking speed, stride length, and stride frequency during the blindfolded condition compared with the conditions of normal vision and virtual reality. Second, we expect that older adults will modulate their walking performance and heading direction to a greater extent in response to changes in optic flow speed and lateral flow asymmetry than younger adults. Third, for both younger and older adults, we hypothesize that walking speed, stride length, and stride frequency will be modulated linearly with manipulations of optic flow speed during overground walking. For example, increasing optic flow speed will result in a reduced walking speed, stride frequency, and stride length. It is also expected that the interlimb coordination will demonstrate a change from a 1:1 to a 2:1 arm-and-leg frequency ratio with increasing

optic flow speed. Finally, with regard to heading direction, it is hypothesized that participants will drift away from the wall that is moving faster, and the degree of lateral drift will be proportional to the level of lateral flow asymmetry.

METHODS

Participants

The participants consisted of two groups: 16 younger adults (8 men, 8 women; 15 right-handers, 1 left-hander; mean age 22.2 ± 3.4 years; age range 18–30 years) and 17 older adults (8 men, 9 women; 16 right-handers, 1 left-hander; mean age 60.5 ± 8.7 years, age range 46–73 years). Older adults were recruited through local newspaper advertisements and personal contacts, and younger adults were undergraduates at Boston University. Exclusion criteria included walking disability or history of leg, knee, hip impairments, serious cardiac disease, other serious chronic medical illness, history of traumatic brain injury, psychiatric or neurological diagnoses, history of alcoholism or other drug abuse, or history of eye disease or other abnormalities as noted on neuro-ophthalmological examination. Individuals whose corrected binocular acuity was poorer than 20/40 were excluded. Informed consent approved by the Institutional Review Board of Boston University and conforming to the 1964 Declaration of Helsinki was obtained prior to participation. All participants were paid for participation.

Material

The VR system.—A virtual hallway was created using World ToolKit Release 9 (Sense8, San Francisco, CA) on an Onyx2 Reality graphics work station (Silicon Graphics, Inc., Mountain View, CA). The hallway was composed of two sidewalls of white random dots on a black background (Figure 1). The width of the hallway was 2 m, the height of the hallway 2.55 m, and the depth of the hallway 8.88 m. The middle of the virtual hallway along the anteroposterior axis was always aligned with a reference axis in the real environment. The orientations of the virtual hallway in the frontal and sagittal planes were calibrated with respect to each participant's head orientation, whereas the participant was instructed to stand upright and face forward. The visual scene was displayed on a ProView 60 head-mounted display (HMD; Kaiser Opto-Electronics, Inc., Mountain View, CA) weighting 1.75 lbs. This HMD contained two active LCD panels (640×480 resolution, true color, 60 Hz) and had a 60° field-of-view (diagonal) with 100% overlap to allow for true stereo viewing. Participant's field of view was restricted to the VR environment by a mask that occluded vision outside the LCD panels. Head coordinates were tracked in real time, using an IS 900 LAT system (InterSense, Burlington, MA), and the information was used to update the visual scene with a delay of four frames (67.7–83.3 ms). The movement tracking system covered the

overground walking area with an approximate error of less than 4 mm root mean square for position data and 0.1° for orientation data. The optic texture of the virtual hallway's walls in the anteroposterior direction could be manipulated by a computer. The validity of this VR simulation has been demonstrated by Giphart, Chou, Kim, Bortnyk, and Wagenaar (2007).

Three-dimensional kinematics.—Three-dimensional kinematic data were collected using an Optotrak 3020 System (Northern Digital Inc., Waterloo, ON, Canada), with a spatial resolution of 0.1 mm. One position sensor was placed on each side of the walkway, and a third position sensor was located at the end of the walkway in order to provide an environmental reference plane for capturing bilateral locomotor movements for at least eight strides. Calibrations among the three position sensors were accepted when the mean error was 1.5 mm or less. Infrared light-emitting diodes (IREDs) were placed on participant's chin (lower mandible) and bilaterally on the ankle (lateral calcaneus), hip (anterior superior iliac spine), wrist (radiocarpal joint), and shoulder (humeral head). The instantaneous position of each IRED was sampled at a rate of 100 Hz and stored to disk for further analysis.

Experimental Procedure

After intake, three experimental conditions were carried out in a fixed order, that is, Trial 1 (manipulation of vision), Trial 2 (manipulation of optic flow speed), and Trial 3 (manipulation of lateral flow asymmetry). The experimental procedure was described as follows.

Intake.—Visual dependence was assessed by using a rod and frame test (Azulay, Mesure, Amblard, & Pouget, 2002). Participants were presented with a 1.5-m horizontal line that was slightly tilted at the outset of each run (initial tilt ranging from 9° to 12°) in a large screen. The angle of the line was gradually altered to become more horizontal by 1° increments. Participants were asked to indicate when the rod was horizontal. Mean deviation (degree) averaged from 10 runs was taken as the measure of the participants' level of visual dependence. All stimuli sequences were created using Adobe Photoshop and PowerPoint for presentation.

Trial 1.—Participants were trained to walk 8 m at 0.8 ± 0.05 m/s because the state of interlimb coordination at this walking speed is relatively unstable (Wagenaar & van Emmerik, 2000). Therefore, if there were any changes in coordination pattern as a result of changes in optic flow speed, it would be observed more sensitively. Three vision conditions were presented in a fixed sequence: (1) eyes opened (EO) condition—participants were instructed to walk down the middle of a walkway in the laboratory with eyes open; (2) blindfolded (BF) condition—participants were instructed to

walk down the middle of the walkway in the lab blindfolded; (3) virtual reality (VR) condition—participants were instructed to walk down the middle of a virtual hallway created by the virtual reality system. In the VR condition, the optic flow speed was set by feedback control to equal -1 times the participant's walking speed in the anteroposterior direction. The minus sign indicated that the optic flow was programmed to move in a direction opposite to the participant's walking direction. Participants had the opportunity to practice walking in the virtual environment for at least 10 min, until they demonstrated that they were able to walk comfortably at 0.8 ± 0.05 m/s. For each condition, at least five runs were performed. Each participant received feedback on walking speed after each run. The average walking speed was measured in real time with two sets of infrared switches (Safe House, Fort Worth, TX) placed 6 m apart along the walkway.

Trial 2.—Five different optic flow speed conditions (0, -0.4 , -0.8 , -1.2 , and -1.6 m/s) were presented in random order across participants. Five consecutive runs were performed for each optic flow speed condition, yielding 25 runs in total for each participant. Participants were instructed to walk at 0.8 m/s throughout the experimental session. During Trials 2 and 3, the speed of optic flow was held constant within a condition and not a function of the participant's walking speed. For example, when the optic flow speed was -0.8 m/s, participants had the impression that they were walking at the trained speed through a stationary hallway; when the optic flow speed was faster/slower than -0.8 m/s, participants had the impression that they were walking more quickly/slowly than the trained speed. A special case was that when the optic flow speed was equal to 0 m/s, participants had the impression that they were not moving forward relative to the hallway, even though they were walking (i.e., a situation similar to that experienced visually during walking on a treadmill). No feedback on walking speed was provided during Trials 2 and 3.

Trial 3.—Participants were trained to walk at 0.8 ± 0.05 m/s again in the VR environment for at least five runs prior to Trial 3. In Trial 3, the optic flow speed in one visual field was always equal to -0.8 m/s, whereas the flow speed in the other visual field was 0, -0.4 , -0.8 , -1.2 , or -1.6 m/s. The 10 different optic flow speed conditions were presented in random order across participants. Five runs were performed for each condition, yielding 50 ($2 \times 5 \times 5$) runs in total for each participant.

Data Analysis

For kinematic analysis, the position data were filtered using a zero-lag, fourth-order Butterworth low-pass filter with a cutoff frequency of 5 Hz. Shoulder and wrist time series were used to compute the angular displacement of arm movements and hip and ankle time series to calculate the angular

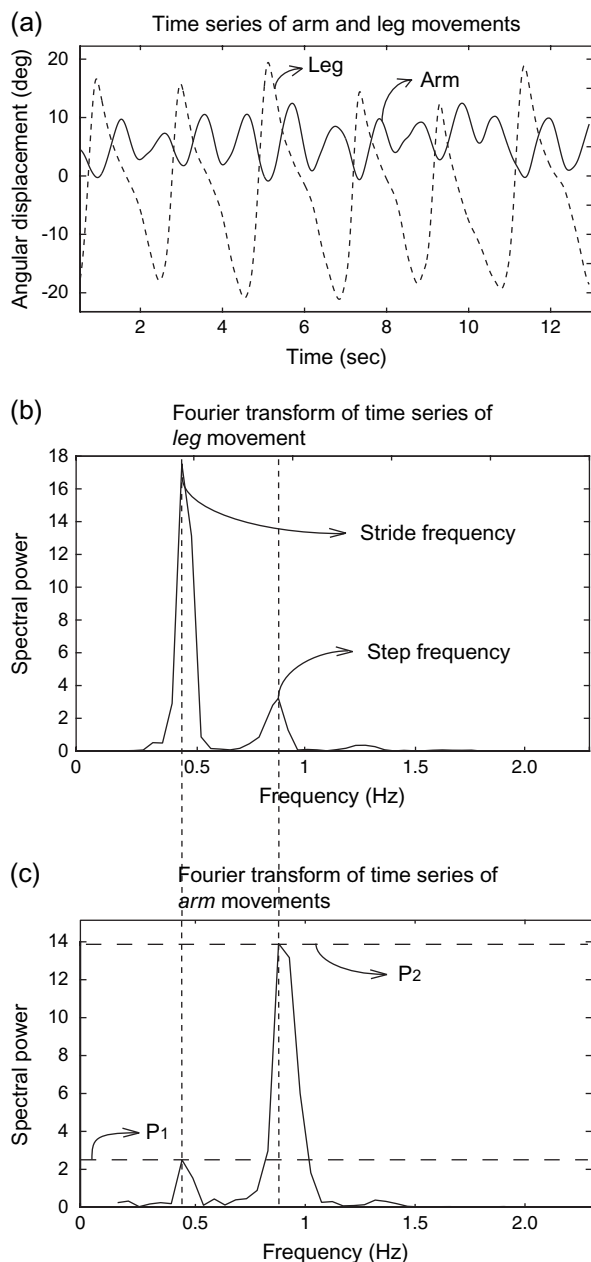


Figure 2. Fourier transform of time series of arm and leg movements.

displacement of leg movements relative to vertical. Forward wrist or ankle movement resulted in a positive angle. Each stride cycle was identified by two consecutive maxima from the angular position data of leg movements. All the variables were computed for only the middle six strides in order to avoid acceleration and deceleration variations at the beginning and at the end of the distance walked. The data were processed using MatLab (The MathWorks, Inc., Natick, MA).

Walking speed and stride parameters.—The average walking speed was estimated by the displacement of the chin time series in the anteroposterior axis divided by the

time it took the participant to travel for six stride cycles. Stride length was calculated from both the left and right ankle time series, separately, by dividing the displacement in the anteroposterior axis divided by 6 (i.e., the number of strides). Stride frequency was calculated in strides per second (as the inverse of the time it took the participant to travel six stride cycles divided by the number of strides).

Relative power index.—The angular displacement data of the arm and leg movements were used for the analysis of interlimb coordination. Figure 2a shows an example of the time series data of arm and leg movements during walking at lower speeds. The power spectral density function was used to transform the time series data into movement frequencies and corresponding spectral power for leg (Figure 2b) and arm movements (Figure 2c). The spectral power was normalized by dividing each frequency power by the mean power calculated over the 0.2- to 2.5-Hz frequency range for each run.

A step is heel contact of one leg to heel contact of the other leg, a stride from heel contact to heel contact of the same leg. As in Figure 2b, the frequency with the largest power was regarded as the stride frequency (Wagenaar & van Emmerik, 2000). The step frequency was the peak at twice the stride frequency. The corresponding power at the stride and step frequencies of arm movements was identified using the stride and step frequencies from the leg movements, respectively (see Figure 2c). To quantify the frequency ratio of arm and leg movements, a relative power index (RPI) was calculated using the following Equation:

$$\text{RPI} = \frac{P_1 - P_2}{P_1 + P_2},$$

where P_1 is the power at the stride frequency observed in the arm movements and P_2 is the power at the step frequency observed in the arm movements (Figure 2c). RPI ranges from -1 to 1 . RPI equal to 1 indicates a $1:1$ frequency ratio between arm and leg movements. RPI equal to -1 points out a $2:1$ coordination pattern in which the arms cycle twice during every stride cycle of the legs.

Drift.—The average of left and right hip position data in the mediolateral axis was used as the body reference point. The drift is defined as the difference in mediolateral coordinates between the last and the first stride. A positive value indicates rightward drift and a negative value indicates leftward drift. Each participant's drift data in Trials 2 and 3 would be normalized by his or her baseline measures of drift in the VR condition during Trial 1.

Statistical Analysis

Visual dependence.—The difference of visual dependency between the older and younger adults was examined using a one-way analysis of variance.

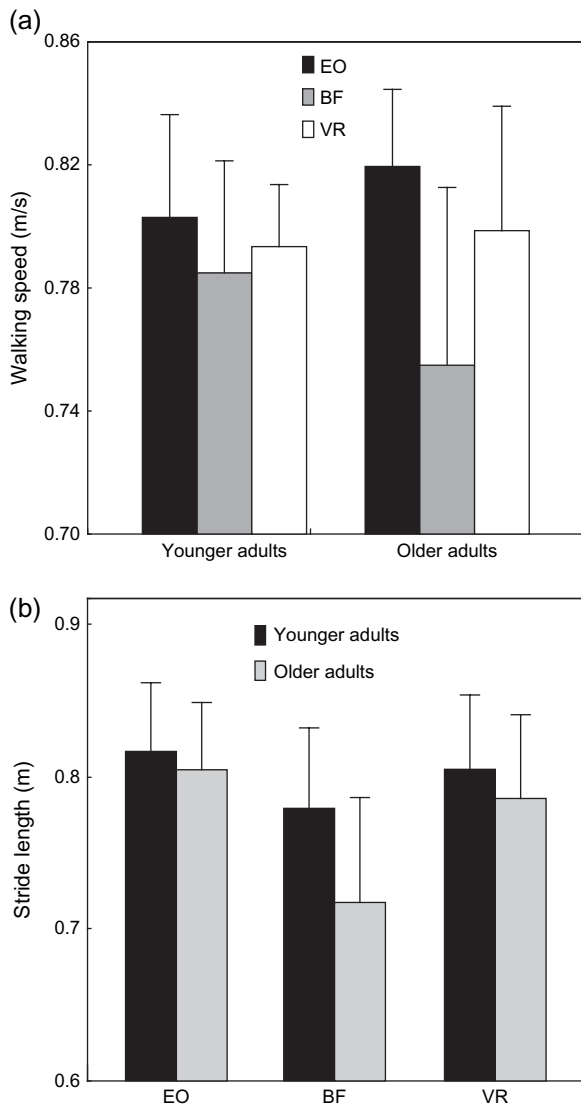


Figure 3. Influence of vision condition on (a) walking speed and (b) stride length in younger and older adults. Error bars show 95% confidence intervals around the means. EO = eyes opened; BF = blindfolded; VR = virtual reality.

Trial 1: Manipulation of vision.—Data across the five runs were averaged for each condition. Whether the average walking speed in the older adults and the younger adults was significantly different from 0.8 m/s was evaluated by means of Wilcoxon one-sample signed-rank tests (with a two-tailed level of significance $\alpha = .05$). In order to test whether there were significant effects of group and vision conditions, a general linear model was performed with a within-subject factor for Vision (EO, BF, and VR) and a between-subject factor for Group (younger and older adults).

Trial 2: Manipulation of optic flow speed.—Data across the five runs were averaged for each condition. A general linear model was performed with a linear contrast for Optic

Flow Speed (within-subject factor, five levels) and a between-subject factor for Group.

Trial 3: Manipulation of lateral flow asymmetry.—Data across the five runs were averaged for each condition. A general linear model was performed with a within-group factor for Visual Field (i.e., optic flow speed changed in the left or the right visual field), a linear contrast for Optic Flow Speed (within-subject factor, five levels), and a between-subject factor for Group.

Post hoc analyses were employed in all three trials in the case of a significant interaction effect or a significant main effect of a variable with more than two levels. Multiple comparisons were conducted with Bonferroni corrections. All analyses were performed using SPSS (SPSS, Inc., Chicago, IL).

RESULTS

There was no statistically significant difference between younger and older adults in visual dependency as measured by the rod and frame task, $F(1, 31) = 0.68$, $p = .42$.

Trial 1: Manipulation of Vision

Walking speed and stride parameters.—The walking speeds in the younger adults were not significantly different from 0.8 m/s (EO: $p = .86$; BF: $p = .15$; VR: $p = .80$). The mean walking speed in the older adults was significantly lower in BF than 0.8 m/s ($p = .03$). However, no significant differences were found for EO ($p = .36$) and VR ($p = .75$). At all conditions, the 95% confidence intervals of the mean walking speed were within 0.8 ± 0.05 m/s for both groups.

Analysis of walking speed yielded a significant main effect for Vision, $F(2, 62) = 18.76$, $p = .0001$, and a significant interaction effect between Vision and Group, $F(2, 62) = 6.33$, $p = .003$ (Figure 3a). Post hoc analyses revealed that a significant effect of Vision was observed in the older adults, $F(2, 32) = 17.97$, $p = .0001$, but not in the younger adults, $F(2, 30) = 2.66$, $p = .09$. Post hoc analyses of the vision effect in the older adults showed that walking speed in BF was significantly lower than that in EO ($p = .0001$) and VR ($p = .006$).

Significant main effects for Vision, $F(2, 62) = 12.38$, $p = .0001$, and Group, $F(1, 31) = 4.42$, $p = .05$, were observed for stride frequency. Older adults had a significantly higher stride frequency (1.10 Hz) than the younger adults (1.03 Hz). Post hoc analyses revealed that stride frequency in BF (1.14 Hz) was significantly higher than that in EO (1.01 Hz, $p = .001$) and VR (1.05 Hz, $p = .001$).

A significant main effect for Vision, $F(2, 62) = 32.12$, $p = .0001$, and a significant Vision \times Group interaction effect, $F(2, 62) = 5.51$, $p = .006$ (Figure 3b) were found for stride length. Post hoc analyses revealed that (1) there were significant differences among vision conditions in the older adults, $F(2, 32) = 22.25$, $p = .0001$, as well as the younger

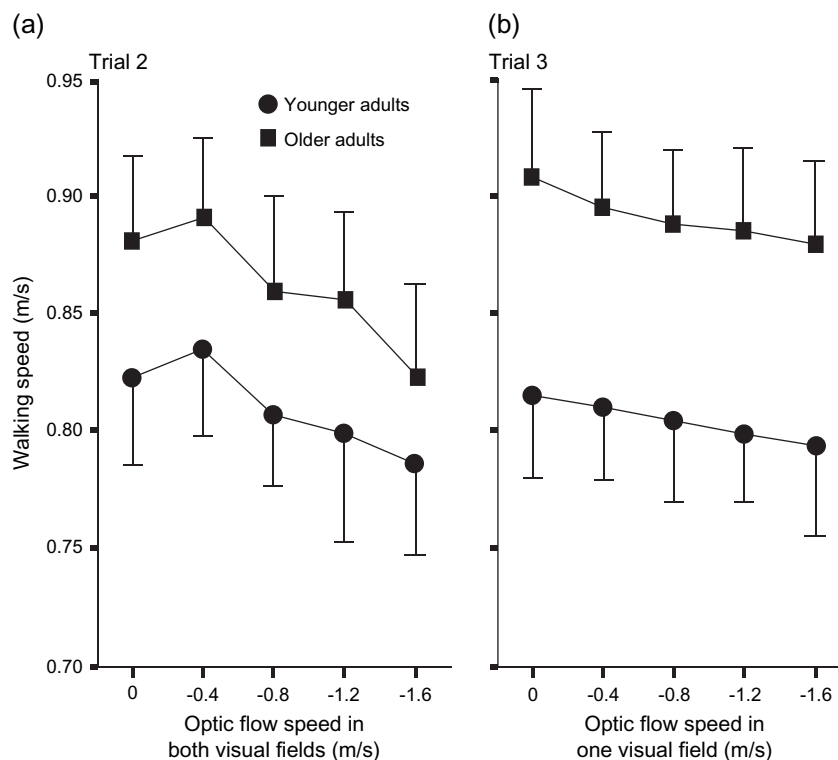


Figure 4. Influence of optic flow speed on walking speed in (a) Trial 2 and (b) Trial 3. Error bars show 95% confidence intervals around the means.

adults, $F(2, 30)=11.24$, $p=.0001$, and (2) the group effect was significant only in BF, $F(1, 31)=8.24$, $p=.007$, indicating that the older adults had significantly shorter stride length compared with the younger adults in BF. In addition, both groups showed that the greatest stride length was observed in EO, followed by VR, and then BF.

The RPI.—Analysis of RPI yielded a significant main effect for Vision, $F(2, 62)=3.88$, $p=.03$. Post hoc analyses showed that the RPI in VR (0.74 ± 0.34) was significantly greater than that in EO (0.65 ± 0.33 , $p=.03$).

Drift.—A significant main effect for Vision, $F(2, 62)=4.51$, $p=.02$, was found. The average drifts are 32.30 ($SD=50.44$), -119.82 ($SD=395.66$), and 32.37 ($SD=62.20$) mm for the EO, BF, and VR conditions, respectively. Post hoc analyses showed no significant effect among the three vision conditions.

Trial 2: Manipulation of Optic Flow Speed

Walking speed and stride parameters.—The linear main effects for Optic Flow Speed were significant for walking speed, $F(1, 31)=16.42$, $p=.0001$, and stride frequency, $F(1, 31)=22.87$, $p=.0001$, indicating that both groups decreased walking speed (see Figure 4a) and stride frequency (see Figure 5a) when the optic flow speed was increased. The main Group effects were significant for walking speed,

$F(1, 31)=6.38$, $p=.02$, and stride frequency, $F(1, 31)=9.52$, $p=.004$, showing that older adults walked at a higher speed (0.86 ± 0.08 m/s) and stride frequency (1.09 ± 0.11 Hz) than the younger adults (0.81 ± 0.08 m/s; 1.00 ± 0.09 Hz, respectively). No significant interaction effects between Group and Optic Flow Speed were found for walking speed, $F(1, 31)=0.42$, $p=.52$, and stride frequency, $F(1, 31)=1.43$, $p=.24$. No significant main or interaction effects were found for stride length.

The RPI.—There was a significant linear effect for Optic Flow Speed, $F(1, 31)=5.73$, $p=.02$ (see Figure 6a). The RPI in both groups decreased with the increment of optic flow speed, and the impacts of Optic Flow Speed on RPI were not significantly different between the older and the younger adults, $F(1, 31)=3.61$, $p=.07$. As shown in Figure 6a, the mean RPIs were positive, indicating that the overall distribution of RPI was confined primarily to the 1:1 frequency ratio.

Drift.—No significant main or interaction effects were observed (Figure 7a).

Trial 3: Manipulation of Lateral Flow Asymmetry

Walking speed and stride parameters.—The linear effects for Optic Flow Speed were significant for walking speed, $F(1, 31)=16.69$, $p=.0001$, and stride frequency,

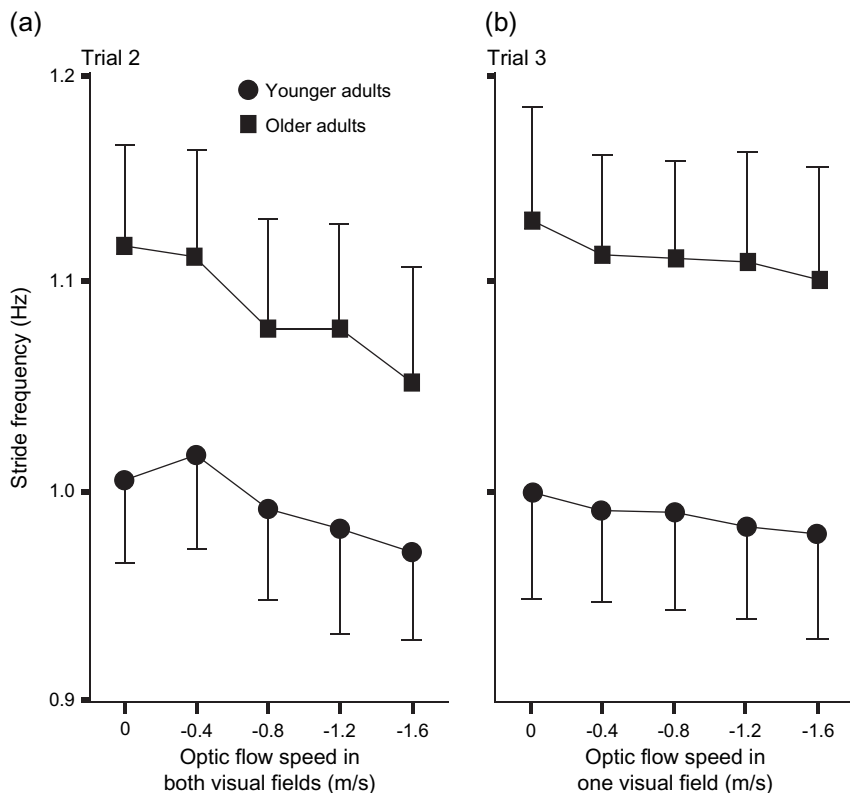


Figure 5. Influence of optic flow speed on stride frequency in (a) Trial 2 and (b) Trial 3. Error bars show 95% confidence intervals around the means.

$F(1, 31) = 11.99$, $p = .0001$, indicating that both groups decreased walking speed (see Figure 4b) and stride frequency (see Figure 5b) when the optic flow speed in unilateral visual field was increased. The Group effects were significant for walking speed, $F(1, 31) = 16.96$, $p = .0001$, and stride frequency, $F(1, 31) = 14.78$, $p = .001$, showing that older adults walked at a higher speed (0.89 ± 0.08 m/s) and stride frequency (1.11 ± 0.11 Hz) than the younger adults (0.81 ± 0.07 m/s; 0.99 ± 0.10 Hz, respectively). No significant interaction effects between Group and Optic Flow Speed were found for walking speed, $F(1, 31) = 0.09$, $p = .76$, and stride frequency, $F(1, 31) = 0.35$, $p = .56$. No significant main or interaction effects were found for stride length.

The RPI.—A significant linear effect for Optic Flow Speed, $F(1, 31) = 7.23$, $p = .01$, was found. The RPI in both groups decreased with the increment of optic flow speed in left or right visual field, and the effects of Optic Flow Speed on RPI were not significantly different between the older and the younger adults, $F(1, 31) = 0.99$, $p = .33$. As shown in Figure 6b, the mean RPIs were positive, indicating that the overall distribution of RPI was confined primarily to the 1:1 coordination pattern.

Drift.—A significant linear effect for Optic Flow Speed was observed, $F(1, 31) = 26.37$, $p = .0001$, indicating that both groups drifted away from the wall that was moving

faster, and the degree of drift was positively related to the difference in optic flow speeds between the two walls (see Figure 7b). The effects of Optic Flow Speed manipulations were not significantly different between the older and the younger adults, $F(1, 31) = 0.04$, $p = .85$. No other significant main or interaction effects were observed.

DISCUSSION

The purpose of the study was to investigate whether older adults show different modulations in locomotion compared with younger adults in response to availability of vision, optic flow speed, and lateral flow asymmetry. The result in Trial 1 corroborates previous findings showing that, in terms of walking speed and stride length, older and younger adults were affected differentially by the availability of vision (Choy et al., 2003; Cromwell et al., 2001, 2002; Hay et al., 1996; Manchester et al., 1989). However, in Trials 2 and 3, the effects of flow speed and lateral flow asymmetry were not influenced by age. Our findings, complementing previous studies (Anderson et al., 1998; Konczak, 1994; Schubert et al., 2005), did not support a greater dependence on optic flow information in older adults during walking. Additionally, no age-related difference was found for the rod and frame test. Taken together, the findings suggest that the ability to integrate optic flow information into the multimodal system for assessment of walking speed and heading direction was comparable in older and younger adults.

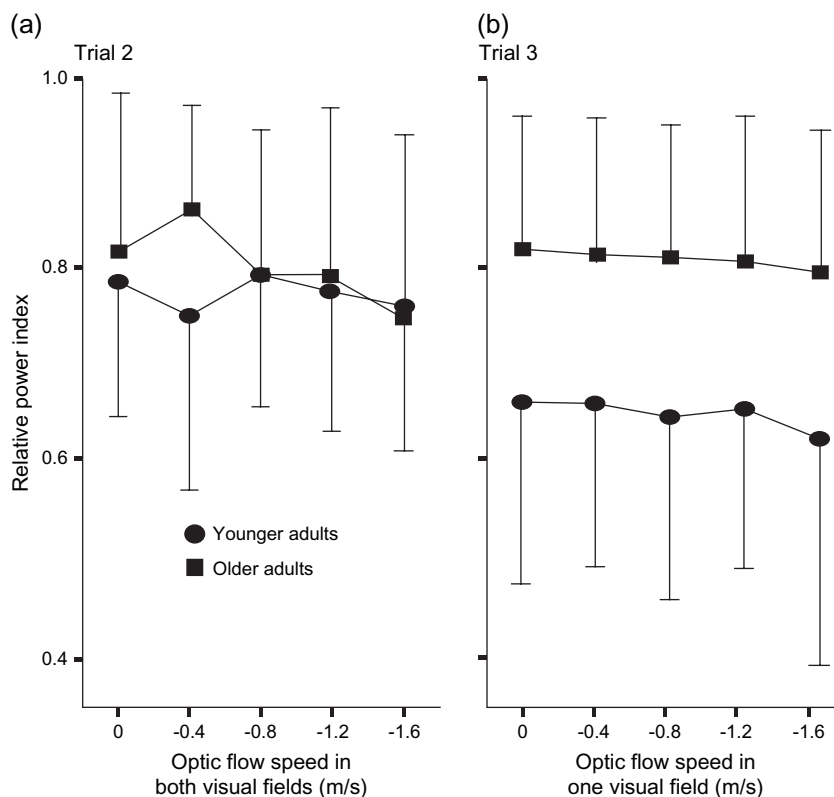


Figure 6. Influence of optic flow speed on relative power index in (a) Trial 2 and (b) Trial 3. Error bars show 95% confidence intervals around the means.

When vision was deprived, adapted walking performance in older adults emerged possibly due to changes in vestibular or somatosensory function or previous experiences, making them walk more cautiously. We are aware that some participants in the older group were younger than 65. Could the insignificant interaction effect between age and optic flow speed be attributed to the existence of subgroups in the older group? We, thus, divided the older group into two by a cut-off age of 65 years and ran the statistical analyses again. The findings with three groups were not different from those with two groups, indicating that this possibility can be ruled out.

Confirming previous results (Prokop et al., 1997; Schubert et al., 2005; Varraine et al., 2002), changes in absolute value of optic flow speed were linearly and negatively correlated with variations in walking speed, stride frequency, and RPI. The finding can be interpreted as that optic flow speed presented in Trials 2 and 3 was compared with the flow speed perceived during training (i.e., -0.8 m/s). When the flow speed was faster/slower than -0.8 m/s, participants felt that they were walking more quickly/slowly than the trained speed, and they modulated locomotion inadvertently or intentionally to keep their walking speed as instructed. Interestingly, even when changes in flow speed occurred in the unilateral wall only, the effects of optic flow speed could still be observed. One possible explanation is that the perceived flow speed might be the average of the flow speeds

from the two walls. More experiments are needed to understand how optic flow speed is perceived when flow speeds are different in two visual fields.

With respect to the effects of lateral flow asymmetry, participants drifted away from the wall that was moving faster, and the degree of drift was positively related to the difference of optic flow speeds between the two walls. This agrees with data from previous studies (Duchon & Warren, 2002; Srinivasan et al., 1991), suggesting that when optic flow speeds are different in two visual fields, participants consider their trajectory as curved and would drift to a balance point at which the flow speed in both sides appears equal.

In all, 30 of 33 participants retained a pattern of 1:1 arm-to-leg frequency ratio across all conditions and did not show any transitions with the manipulations of optic flow speed. This finding suggests that optic flow speed may not be an appropriate control parameter for changes in interlimb coordination during walking. However, it may also be the case that walking overground at 0.8 m/s reduced the likelihood of finding effects of optic flow speed manipulations on interlimb coordination. It appears that more stable patterns (i.e., 1:1 arm-to-leg frequency ratio) were observed during overground walking at 0.8 m/s than during treadmill walking at the same speed, and there is a possibility that the transition point during overground walking is at a lower walking speed compared with treadmill walking. Future work on interlimb coordination during overground walking with

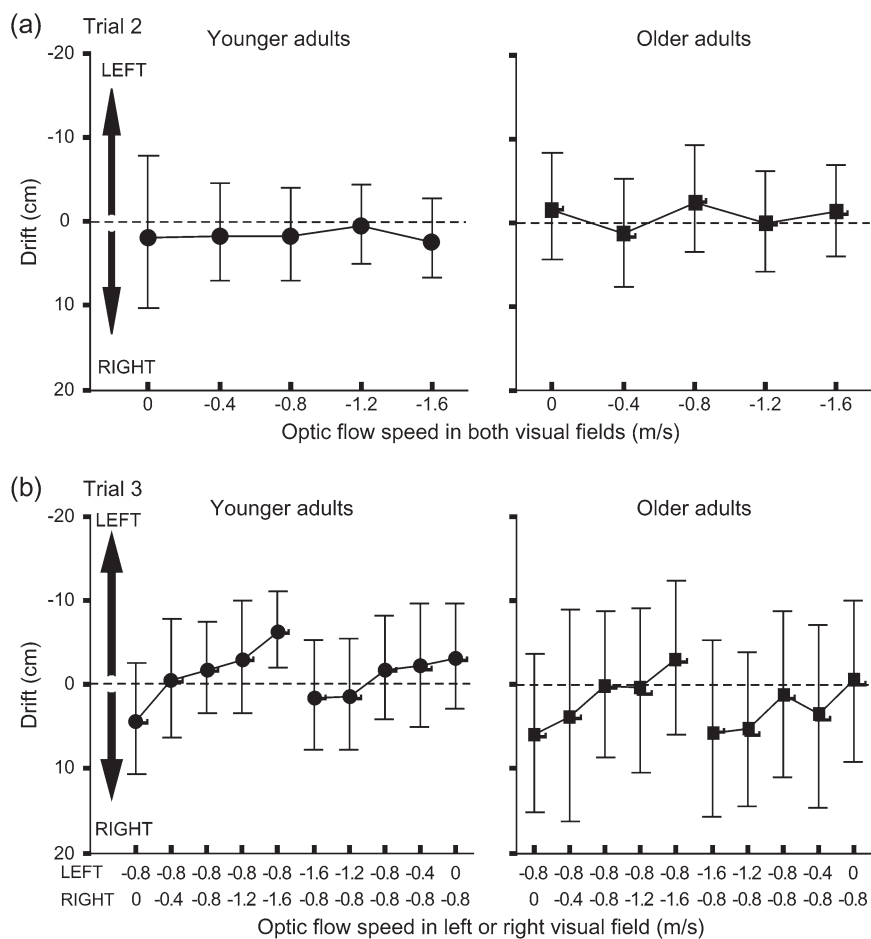


Figure 7. Influence of optic flow speed on drift in (a) Trial 2 and (b) Trial 3. Error bars show 95% confidence intervals around the means.

a systematic manipulation of walking speed will provide further insight into coordination dynamics.

Older adults walked significantly faster than younger adults in Trials 2 and 3, but not in Trial 1. There are two possible explanations. First, the reported preferred walking speed was between 0.82 and 1.38 m/s for older adults and around 1.20 m/s for younger adults (Malatesta et al., 2004; McGibbon & Krebs, 2001; Patel et al., 2006). Because the trained walking speed might not be the preferred walking speed for all the participants, older adults who could not maintain the muscle strength needed for smooth walking at 0.8 m/s, or found the exposure to the VR environment challenging (Giphart et al., 2007), might have unintentionally walked at their preferred speed to reduce gait variability (i.e., to improve stability). Second, it has been reported that the perceived speed reduced after prolonged exposure to optic flow (Krekelberg, van Wezel, & Albright, 2006; Smith, 1985). It is possible that the perceived speed in older adults was lower than that in younger adults after adaptation, thereby inducing higher walking speeds in older adults. Further studies are needed to test these hypotheses.

In the current study, we provide evidence that older adults are able to integrate optic flow information into the multimodal system to monitor their walking speed and heading direction in much the same manner as younger adults. Future research on the fall-prone elderly is needed to understand whether perception of optic flow is degraded in this population and how they use the optic flow information to guide locomotion.

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