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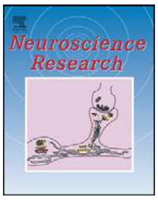

# Visual control of walking velocity

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ABSTRACT

Even if optical correlates of self-motion velocity have already been identified, their contribution to the control of displacement velocity remains to be established. In this study, we used a virtual reality set-up coupled to a treadmill to test the role of both Global Optic Flow Rate (GOFR) and Edge Rate (ER) in the regulation of walking velocity. Participants were required to walk at a constant velocity, corresponding to their preferred walking velocity, while eye height and texture density were manipulated. This manipulation perturbed the natural relationship between the actual walking velocity and its optical specification by GOFR and ER, respectively. Results revealed that both these sources of information are indeed used by participants to control walking speed, as demonstrated by a slowing down of actual walking velocity when the optical specification of velocity by either GOFR or ER gives rise to an overestimation of actual velocity, and *vice versa*. Gait analyses showed that these walking velocity adjustments result from simultaneous adaptations in both step length and step duration. The role of visual information in the control of self-motion velocity is discussed in relation with other factors.

## 1. Introduction

How do we control our walking speed? Over the last 60 years, a large number of studies have explored the nature of the perceptual-motor dialogue involved in many locomotory activities (Warren, 1998). These studies have provided not only a description of perceptual information involved in the execution of these tasks, but also models linking these sources of information to movement (called ‘laws of control’). Surprisingly, the issue of the control of self-motion velocity and more precisely the role of the optical correlates of displacement velocity in the control process is still open to debate. An overview of existing findings is provided in the following sections.

Locomotion speed has been shown to depend mainly on two kinds of factors, including biomechanical constraints and perceptual information. The role of biomechanical constraints has been elegantly demonstrated for many living agents: Kugler and Turvey (1987) found that in many species the preferred stride frequency of walking and consequently preferred walking speed is determined to a large degree by lower-limb pendulum dynamics. The origin of such species-dependent walking behavior should be rooted in the optimization of several kinematic (e.g., angular accelerations of ankle; Hreljac, 1995) and biomechanical factors (e.g., prevention of stress in the dorsiflexor muscles of ankle; Hreljac, 1995). However, in addition to the influence of such permanent constraints on locomotion behavior (i.e., at the time scale of life-long development), perceptual information has been demonstrated to contribute continuously (i.e., at the time scale of a perceptual-motor loop) to the adaptive control of locomotion. For instance, limb proprioception has been experimentally demonstrated to influence the control of locomotion velocity. Indeed, during a blindfolded forward walk at constant velocity, participants respond to hamstrings vibration, giving rise to an illusory backward displacement of the centre of mass, by an increase in velocity (Ivanenko et al., 2000). Visual information has also been shown to play a major role in the control process of locomotion velocity (Warren, 1998). In the majority of the recent studies on this topic, the ingenious methodological feats of earlier studies (e.g., Rieser et al., 1995) have been replaced by virtual reality technologies (e.g., Pailhous et al., 1990; Konczak, 1994; Prokop et al., 1997; Mohler et al., 2007) that provide a powerful tool to examine the underlying perceptual-motor dialogue between optics and behavior. Pailhous et al. (1990) instructed their participants to maintain a constant walking velocity in different visual flow conditions. During the experiment the gain between the actual walking speed and its visual consequences was manipulated. Participants were found to decrease their walking velocity when the gain was >1, whereas no changes occurred when the gain was <1. Comparable results have been reported in different experimental setups, including projection on a half-spherical screen (Prokop et al., 1997) and walking through a virtual hallway (Konczak, 1994) or walking on a self-driven treadmill (Mohler

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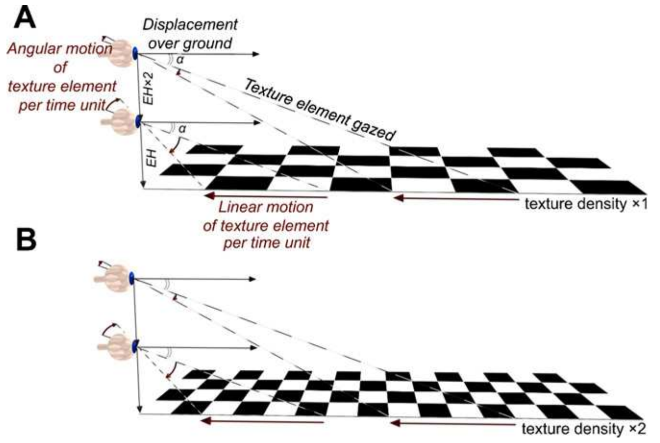

**Fig. 1.** Consequences of eye height (*EH*) and texture density manipulations on the two identified optical sources information specifying locomotion velocity (GOFR: Global Optic Flow Rate; ER: Edge Rate) for a moving observer. GOFR is the angular velocity of texture elements in a given visual direction ($\alpha$). ER is the number of texture elements per unit of time that pass by a reference point in a given visual direction. (A) When increasing *EH* (here 2×), GOFR specifies a slower velocity but ER is not affected. (B) When increasing the texture density (here 2× regarding), GOFR is not affected but ER specifies a faster velocity (adapted from Fajen, 2005).

et al., 2007). Visual information has also been reported to influence the walk-to-run and run-to-walk transitions (Mohler et al., 2007). Participants were required to walk on a treadmill whose velocity was gradually increased or decreased. Once again the gain between the participants' locomotor speed and its visual consequences was manipulated (using gains equal to 2 or 0.5 relative to the control gain of 1). Walk-to-run transitions occurred at a lower velocity (2.04 m/s) in the condition with a gain equal to 2 than in the control condition (2.11 m/s), whereas the inverse pattern was obtained in the condition with a gain equal to 0.5 (2.18 m/s). Similar results were obtained for the run-to-walk transitions.

This short overview of the literature clearly indicates that walking speed is influenced not only by biomechanical constraints but also by proprioceptive and visual information. The present study focused on visual information in order to provide a more detailed understanding of the different optical sources of informations involved in the regulation of walking velocity. Indeed, even if the studies discussed above unambiguously demonstrate the functional role played by optic flow in the control of displacement velocity, they have not allowed the identification of the pertinent properties of the optic flow. Put differently, more fine-grained manipulations of the optic flow – going beyond a mere change in gain – should allow to pinpoint the optical flow characteristics involved in the control of displacement velocity.

Larish and Flach (1990) demonstrated that self-motion velocity was specified by (at least) two properties of the optic flow, Global Optic Flow Rate (GOFR) and Edge Rate (ER). Both GOFR and ER are proportional to ground speed. GOFR, a term first coined by Warren (1981), corresponds to the rate of optical motion of texture elements along a given visual direction. It captures the ratio of horizontal speed over height and is expressed in radians per second. GOFR is dependent on eye height and independent of texture density (Fig. 1). ER corresponds to the number of texture elements that pass by the observation point in a given visual direction in a unit of time and is expressed in edges per second. ER is independent of eye height and dependent on texture density (Fig. 1). In Larish and Flach's (1990) experiments, participants were asked to perform magnitude judgements of self-motion velocity in a simulated environment while ER and GOFR were manipulated. The results demonstrated that ER and GOFR have additive effects on magnitude judgments of self-motion velocity. Increasing ER, GOFR, or both resulted in increasing speed estimates. Moreover the authors showed that ER dominated GOFR in judgements of speed. This study therefore suggests that these two properties of optic flow are indeed used by participants to judge their displacement velocity, at least when exposed to an optic flow simulating self-motion (i.e., passive stimulation).

Are these two properties of the optic flow also used by participants to control their velocity while performing a perceptual-motor task? Fajen (2005) reported a series of experiments exploring the visual control strategies underlying emergency braking. In these experiments GOFR was manipulated by changing eye height and ER was manipulated by changing the density of ground-texture elements, achieved by changing the size of bricks constituting the ground-texture. Fajen's (2005) results revealed that when eye height was increased (i.e., GOFR decreased) and/or texture density decreased (ER decreased), braking was initiated later in comparison with the control condition and, as a consequence, participants tended to crash into the target. Conversely, braking was triggered earlier and participants undershot the target in the opposite conditions.

Thus, both GOFR and ER appear to be used in judging self-motion speed as well as in triggering emergency braking, even though the contribution of each source of information might depend on the task at hand. In the current study we examined the role of these two sources of information in the control of locomotion velocity in a task requiring participants to walk at their preferred speed. We hypothesized that participants should decrease their walking velocity when the optical specification of displacement velocity by either GOFR or ER was higher than the actual displacement velocity and *vice versa*. Biasing the optical specification of locomotion velocity by GOFR was achieved by manipulating eye height. We hypothesized that if GOFR is used to control displacement speed, the participants should modify their walking speed so as experience the same resulting optical velocity as that experienced during walk in the control condition (actual eye height) or at least to minimize the differences. They should decrease their velocity when eye height is decreased and *vice versa*. Biasing the optical specification of locomotion velocity by ER was achieved by manipulating texture density. We hypothesized that if ER is used to control displacement speed, participants should either decrease or increase their velocity when texture density was either increased or decreased so as to experience the same rate of local discontinuities or at least to minimize the differences with the control condition (intermediate texture density).

## 2. Materials and methods

Eight participants (22.4 ± 1.4 years old) with normal or corrected to normal vision volunteered for participation in the present study. A local ethics committee approved the experimental protocol. The virtual reality set-up (Fig. 2A) consisted of two host computers, a treadmill (Sprint, Medical Development, Tecmachine filiale HEF, Andrézieux Bouthéon, FR), a Barco video-projector (BARCO IQ R500, Patay, FR), and a 2.3 m high × 3.0 m wide projection screen (Procolor SAS, FR). The participants walked on the treadmill, equipped with a 0.49 m wide × 1.82 m long moving belt sliding over a flat and rigid surface, and wore earmuffs in order to avoid the potential use of auditory information on walking speed emanating from the treadmill or from treadmill to foot contacts. Participants were attached to the back of the treadmill by means of a weight-lifting belt and a rigid rod allowing small vertical and sideward movements when walking. This set-up allowed participants to exert horizontal forces on the treadmill belt so as to regulate walking speed. The velocity of the treadmill belt was sampled *via* an optical encoder (200 Hz) and sent to the first host computer that monitored walking velocity and computed the position of participants in the virtual scene on-line. Virtual position was sent by

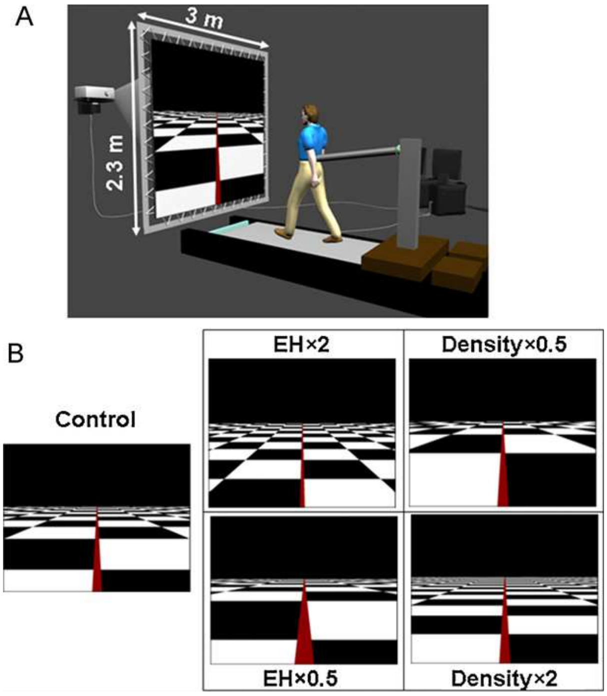

**Fig. 2.** (A) Experimental setup. The virtual reality set-up consisted of two host computers, a treadmill, a video-projector, and a large projection screen. The participants walked on the treadmill, equipped with a moving belt sliding over a flat and rigid surface. Participants were attached to the back of the treadmill by means of a weight-lifting belt and a rigid rod allowing small vertical and sideward movements when walking. (B) Screenshots of the virtual environment depicted during the different experimental manipulations of Global Optic Flow Rate and Edge Rate conditions as compared to the *Control* condition. Increasing eye height (*EH* × 2) or decreasing texture density (*Density* × 0.5) was expected to lead to a decrease in perceived displacement velocity. Decreasing eye height (*EH* × 0.5) or increasing texture density (*Density* × 2) was expected to lead to an increase in perceived displacement velocity.

an RS-232 serial port to the second host computer that rendered the corresponding visual scene. Images were back-projected by the video-projector (refresh rate 60 Hz) onto the screen, placed 0.70 m in front of the participants (providing a 117° × 130° field of view). The scene consisted of a textured ground plane made up of black and white squares (1.15 m wide × 1.15 m height) and a 0.1 m wide red displacement axis. The end-to-end latency of the virtual set-up was estimated to be at maximum equal to 30 ms.

Before beginning the experiment, participants were asked to walk at least 5 min on the treadmill in order to familiarize themselves with the apparatus. Participants were then asked to walk as naturally as possible at preferred speed during 3 min in order to record their preferred walking velocity.

The experiment consisted of two successive walking phases (denoted *preparation* and *test*), separated by a 30 s rest period during which participants stood upright in the dark. In the *preparation* phase, participants were asked to walk at an imposed velocity corresponding to either 80% 100% or 120% of their preferred velocity during 2 min. Visual feedback was provided when they deviated from the required velocity more than a criterion of 2.5 times the standard deviation computed from their recorded preferred velocity signals. The visual scene was tinted either red or green when walking velocity was too high or too low, respectively. The goal of the *preparation* phase was essentially methodological. Several blind-walking experiments have revealed that participants could use non-visual sensory signals either to walk accurately towards a previously seen target or to produce a previously learned displacement velocity (Thomson, 1983). By imposing different walking velocities during the preparation phase, we sought to destabilize the non-visual (e.g., proprioceptive) calibration of the preferred walking velocity and we expected the participants to rely more heavily on the visual information available during the completion of the *test* phase, when they were asked to produce their preferred walking velocity.

During the following *test* phase, participants were instructed to reproduce their preferred walking velocity during 2 min. In this phase we either manipulated the participant's eye height (2 modalities) or the texture density of the floor (2 modalities). Eye height was either divided by two (giving rise to a GOFR-based overestimation of self-motion velocity, *EH* × 0.5 condition) or multiplied by two (giving rise to a GOFR-based underestimation of self-motion velocity, *EH* × 2 condition). Along the same logic, texture density was either divided by two (giving rise to a ER-based underestimation of self-motion velocity, *Density* × 0.5 condition), or multiplied by two (giving rise to a ER-based overestimation of self-motion velocity, *Density* × 2 condition). In the *Control* condition the eye height corresponded to the participants' actual eye height and an intermediate texture density (0.75 rectangles/$\text{m}^2$) was provided to the participant, allowing a potentially perfect estimation of self-motion velocity. It is worthnoting that participants were also exposed to these visual conditions (i.e., normal eye height and intermediate texture condition) during the preparation phase.

These manipulations gave rise to five Environment conditions (*EH* × 0.5, *EH* × 2, *Density* × 0.5, *Density* × 2 and *Control*). The 15 experimental conditions (3 Preparations × 5 Environments) were repeated 3 times each, for a total of 45 trials per participant. The order of presentation of the trials was randomized. In each walking phase (*Preparation* and *Test*), participants were required to count various rectangular objects appearing randomly either on the right hand side or on the left hand side of the visual scene. Again the aim of the procedure was to prevent the participants from using a cognitive strategy to control their displacement pace (e.g., counting the step number for a given distance), and to force them to rely predominantly on the perceptual (visual) information available. The velocity, size, time of appearance, and number of the rectangular objects to be counted were randomized across trials.

Analysis focused on four dependent variables: variability of walking velocity, average walking velocity, step length and step duration. Gait variables were extracted from velocity signals provided by the treadmill. We assumed that each local minimum in the belt's velocity profile corresponded to a foot making contact with the treadmill, with a step thus being defined by two consecutive local velocity minima. Step duration was computed as the time span between two consecutive local minima in the belt's velocity. Step length was computed by integrating the velocity profile over this duration. For each participant in each condition, these variables were computed for 10 consecutive blocks of 10 s duration, excluding the first and last 10 s of the 2 min test trials. Data were analyzed using ANOVAs with repeated measures on the factors Preparation (3 levels: 80%, 100%, 120% of preferred velocity), Environment (5 levels: *EH* × 0.5, *EH* × 2, *Density* × 0.5, *Density* × 2 and *Control*) and Block (10 levels) factors. Significant ($P < 0.05$) main effects and interactions were examined using Newman–Keuls post hoc tests.

## 3. Results

The ANOVA on the variability of walking velocity did not reveal any significant main effects (all $P$'s > 0.05) of the factors Preparation, Environment or Block, indicating that the stability of walking behavior did not vary systematically across experimental conditions nor over the duration of a trial.

The ANOVA on walking velocity revealed a significant main effect of Environment ($F_{(4,28)} = 89.69$, $P < 0.05$, $\eta_p^2 = 0.93$) but no main effects of Preparation ($F_{(2,14)} = 0.05$, $P > 0.05$, $\eta_p^2 = 0.01$) and

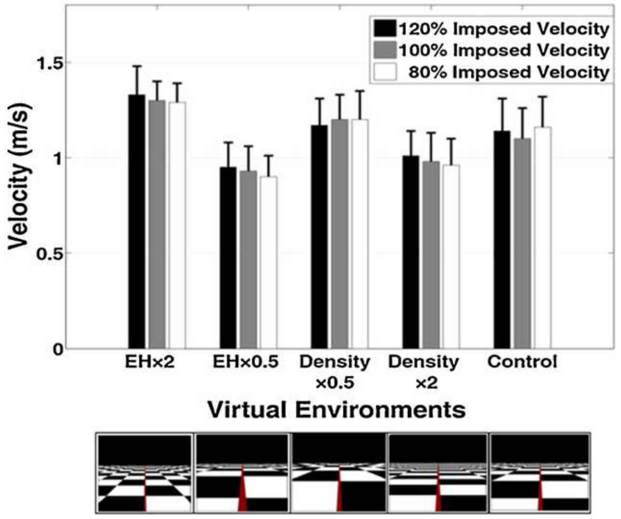

**Fig. 3.** Average between-participant walking velocities during the test phase following three different preparation conditions (imposed velocity equal to 80, 100 and 120% of preferred walking velocity) in the five visual environments (*EH* × 2, *EH* × 0.5, *Density* × 0.5, *Density* × 2 and *Control* conditions). Participants' walking velocity was higher in *EH* × 0.5 and *Density* × 0.5 conditions (1.31 m/s and 1.20 m/s respectively) than in the *Control* condition (1.14 m/s). Participants' walking velocity was lower in *EH* × 2 and *Density* × 2 (0.94 m/s and 0.98 m/s respectively) conditions than in the *Control* condition. Displacement velocity was only marginally affected by the preparation phase conditions. The error bars represent between-participant standard deviations.

Block ($F_{(9,63)} = 1.69$, $P > 0.05$, $\eta_p^2 = 0.19$). The only significant interaction to appear was between Preparation and Environment ($F_{(8,56)} = 2.55$, $P < 0.05$, $\eta_p^2 = 0.27$). This interaction indicated that walking velocity during the *Density* × 2 condition was slightly higher following 120% Preparation than for the two other Preparation conditions (Fig. 3). Moreover, contrary to the other Preparation conditions, under the 120% Preparation condition, the velocity in the *Density* × 0.5 condition did not significantly increase relative to the *Control* condition. However, given that the effect size of this Environment × Preparation interaction was small ($\eta_p^2 = 0.27$) and that it concerned only minor aspects (as revealed by Fig. 3), we focussed on the main effect of Environment ($\eta_p^2 = 0.93$). Post hoc tests indicated that, in comparison to the *Control* condition (mean walking velocity equal to 1.14 m/s), walking velocity significantly ($P < 0.05$) increased in both *EH* × 2 and *Density* × 0.5 conditions. Conversely, walking velocity significantly ($P < 0.05$) decreased in both *EH* × 0.5 and *Density* × 2 conditions. Moreover, GOFR induced larger walking velocity adaptations than ER: walking velocity was higher in the *EH* × 2 than in the *Density* × 0.5 condition (1.31 m/s vs. 1.20 m/s, respectively, $P < 0.05$) and lower in *EH* × 0.5 than in *Density* × 2 (0.94 m/s vs. 0.98 m/s, respectively, $P < 0.05$).

Overall, the observed modifications in walking velocity are consistent with our predictions. The conditions in which the use of either GOFR or ER provided an underestimation of displacement velocity (*EH* × 2 and *Density* × 0.5) gave rise to an increase in displacement velocity (relative to the *Control* condition), while the opposite conditions (*EH* × 0.5 and *Density* × 2) gave rise to a decrease in displacement velocity. Experimental changes in GOFR, *via* manipulation of eye height, gave rise to larger changes in walking velocity (*EH* × 0.5: 16.9%, *EH* × 2 15.0%) than experimental changes in ER, *via* manipulation of texture density (*Density* × 0.5: 5.3%, *Density* × 2: 13.0%).

The ANOVAs on step length and step duration revealed significant main effects of both Preparation ($F_{(2,14)} = 5.85$, $P < 0.05$, $\eta_p^2 = 0.45$ and $F_{(2,14)} = 5.92$, $P < 0.05$, $\eta_p^2 = 0.46$, respectively) and Environment ($F_{(4,28)} = 186.58$, $P < 0.05$, $\eta_p^2 = 0.97$ and $F_{(4,28)} = 178.38$, $P < 0.05$, $\eta_p^2 = 0.96$, respectively), but no significant main effect of Block ($F_{(9,63)} = 1.96$, $P > 0.05$, $\eta_p^2 = 0.21$ and $F_{(9,63)} = 0.94$, $P > 0.05$, $\eta_p^2 = 0.12$, respectively). Step duration was also characterized by a significant Preparation × Environment interaction ($F_{(8,56)} = 5.24$, $P < 0.05$, $\eta_p^2 = 0.43$). As this interaction revealed the same pattern of effects (see Fig. 4) as described for walking velocity, we again focused on the main effects of the experimental factors. Post hoc tests indicated that the main effects of Preparation resulted from a small but systematic increase in step length and step duration in the 120% condition in comparison with the 80% condition (0.61 vs. 0.59 m for step length; 0.67 vs. 0.65 s for step duration, $P$'s < 0.05).

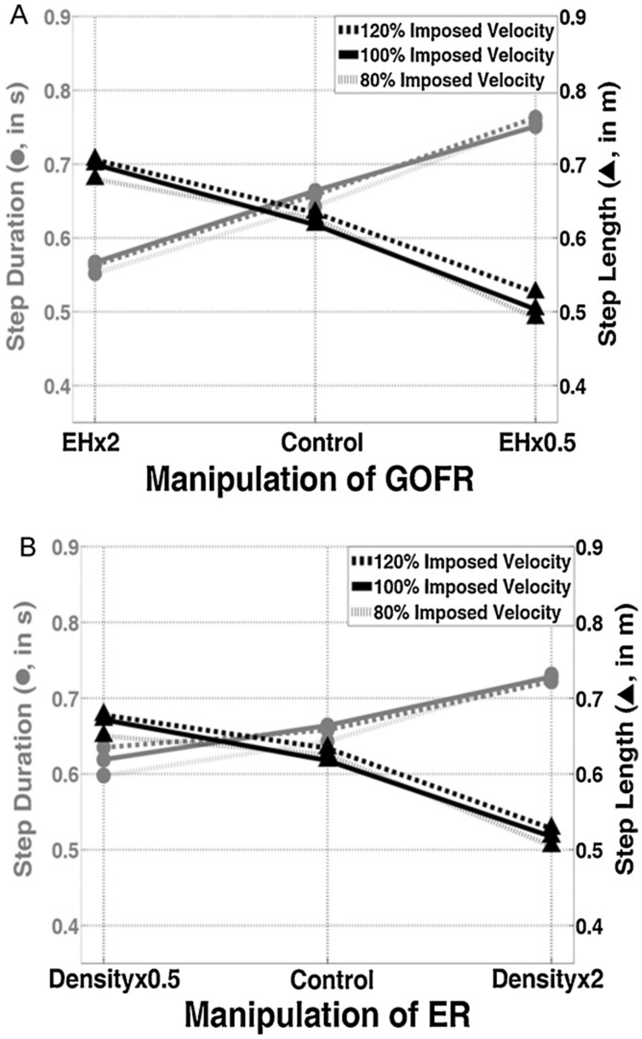

**Fig. 4.** Average between-participant step lengths (▲) and step durations (●) during the test phase following three different preparation conditions (imposed velocity equal to 80, 100 and 120% of preferred walking velocity depicted in dashed, solid and dotted lines, respectively) as a function of (A) GOFR manipulated *via* eye height and (B) ER manipulated *via* texture density. For both types of manipulation (GOFR or ER), step length and step duration are inversely influenced. Step length increases in both *EH* × 2 and *Density* × 0.5 conditions in comparison with the *Control* condition (0.69 and 0.66 vs. 0.62 m, respectively) and decreases in both *EH* × 0.5 and *Density* × 2 conditions (0.51 and 0.51 m vs. 0.62 m). Conversely, step duration decreases in both *EH* × 2 and *Density* × 0.5 conditions in comparison with the *Control* condition (0.56 and 0.61 s vs. 0.65 s, respectively, $P < 0.05$) and increases in both *EH* × 0.5 and *Density* × 2 conditions (0.76 s and 0.72 s vs. 0.65 s, respectively). Both step length and step duration are only marginally affected by the walking velocity imposed during the preparation phase.

Step length and step duration varied systematically as a function of the visual Environment. Post hoc analysis revealed that step length (▲ symbols in Fig. 4) increased in both the *EH* × 2 and