Quelles informations pour réguler les déplacements

2.2. Complémentarité des lois de contrôle

The complementary use of laws of control[10]

ABSTRACT

The aim of this study was concerned with the process by which participants select laws of control in interceptive task while we biased the self-motion velocity. We used a virtual environment coupled with a treadmill to test two perceptual strategies involved in interceptive action: the Constant Bearing Angle (CBA) and the Modified Required Velocity (MRV). We manipulated the curvature of the ball's trajectories and the display of these trajectories. Participants were asked, if necessary, to modify their walking velocity in order to intercept a ball while we biased the self-motion velocity by manipulating the Global Optical Flow Rate (GOFR). Results showed a large effect of the curvature on walking velocity when the trajectory was not displayed, which was a signature of use of the CBA strategy. On the contrary, the walking velocity produced was less affected by displaying the trajectory, which suggested the use of the MRV strategy. Results also showed that biasing the self-motion velocity entailed longer velocity regulations when the MRV strategy was used than when participants used the CBA strategy. However, contrary to the predictions of the MRV model, the effect of the manipulation of GOFR lasted until the middle of the trial and the subjects were able to perform the interception. This suggests that subjects used the MRV model until they realized the failure was imminent and they switched to the CBA model.

[10] François, M., Morice, A.H.P., Bootsma, R.J., Montagne, G. The complementary use of laws of control (*submitted*)

INTRODUCTION

The perceptual control of goal-directed behavior has been addressed in a large set of studies over the last decade. These studies have not only allowed for a better understanding of the perceptual-motor dialogue underlying the control of the action. They have also given rise to the formalization of laws of control proposing unequivocal (and hence testable) accounts of the mutual dependency between motor and perceptual components in different tasks. Conceptually, these laws of control are taken to reflect the operation of organizational (perceptual-motor) principles and theoretically allow several categories of agents to perform a given task under a wide variety of experimental conditions. Morice, Francois, Jacobs et Montagne, (2010) recently questioned the presumed robustness of one such a law of control (known as the Constant Bearing Angle strategy) in the domain of interceptive tasks performed by humans. According to this law of control (Equation 1) (Figure 40A), the strategy of maintaining constant the angle subtended by the current position of the target and the direction of displacement of the observer gives rise to interception of the ball:

$$\ddot{Y} = k_1 \times \frac{1}{1 + 200 \times e^{(-10 \times t)}} \times \dot{\theta} + k_2 \times \dot{Y} \qquad \text{(Equation 1)}$$

In this equation, $\dot{Y}$ is the walking speed (in m/s), $\ddot{Y}$ is the acceleration (in m/s²), $\dot{\theta}$ is the rate of change of the bearing angle (in deg/s, with $\dot{\theta}$ >0 indicating an increase in θ), k1 is a parameter that modulates the strength of the coupling between $\ddot{Y}$ and $\dot{\theta}$, and k2 is a parameter that modulates the strength of the damping term. The function $\frac{1}{1 + 200 \times e^{(-10 \times t)}}$ is an activation function. The damping term with its activation function acts so as to mimic the gradual chacracter of changes in velocity stemming from neurophysiological delays and biomecanical inertia that lead agent to zero out changes in bearing angle in a stable manner.

This law of control has been demonstrated to account for the observed adjustments in walking speed in order to intercept laterally approaching targets under a variety of different task and environment constraints, varying either within or between trials (e.g., Bastin, Calvin, & Montagne, 2006a; Bastin, Craig, & Montagne, 2006b; Bastin, Jacobs, Morice, Craig, & Montagne, 2008; Bastin & Montagne, 2005; Chardenon, Montagne, Buekers, & Laurent, 2002; Chardenon, Montagne, Laurent, & Bootsma, 2004; Chardenon, Montagne, Laurent, & Bootsma, 2005; Lenoir, Musch, Janssens, Thiery, & Uyttenhove, 1999a; Lenoir, Savelsbergh, Musch, Thiery, Uyttenhove, & Janssens., 1999b; Lenoir, Musch, Thiery, & Savelsbergh, 2002).

In a recent contribution however, Morice et al. (2010) provided evidence that participants did not always rely on the CBA strategy. In their study they evaluated the effects of presenting the future spatial path of the ball for different types of ball trajectory (rectilinear or curvilinear). Interestingly, according to the CBA strategy manipulating the curvature of the ball path should influence displacement velocity adjustments in a specific way (cf., Predictions section of Chapter 1, section 3.3.3.2.4). Presenting the future ball path, on the other hand, should not affect the regulation behavior of the participants as this manipulation does not affect the time course of the rate of change in bearing angle. The results speak in favor of the operation of the CBA strategy when the ball path is not depicted, as manipulating the curvature of the ball's trajectory was found to influence displacement velocity adjustments in the way predicted by the CBA strategy. In contrast, when the ball path was depicted the walking kinematics were less affected by the curvature manipulations. Moreover, under those conditions a modified Required Velocity (MRV) strategy (Equation 2 and 3)(Figure 40B) provided a better explanation of the regulation behavior produced by the participants than the CBA strategy:

$$\ddot{Y} = k_1 \times \left(k_2 \times \dot{Y}_{req} - \dot{Y}\right) \qquad \text{(Equation 2)}$$

with

$$\dot{Y}_{req} = \left(Y_{IP} - Y\right)/TTC \qquad \text{(Equation 3)}$$

where Y , $\dot{Y}$, and, $\ddot{Y}$ are the participants' actual position, speed, and acceleration, Y_{req} is the required walking speed, Y_{IP} is the future interception position, TTC is the time remaining before the ball reaches Y_{IP}, and k_1 and k_2 are constants.

The study by Morice et al. (2010) thus allowed circumscribing the field in which the CBA strategy operates, through the identification of boundary conditions; it also provided results compatible with an information-driven switch between two laws of control. Because the MRV strategy (but not the CBA strategy) takes into account the participant's walking speed, a more direct test of the operation of the MRV strategy in informationally-enriched environments can be obtained by manipulating the optical correlates of either participants' current or required speed. The aim of the present study is precisely to question the operation of the MRV strategy, particularly in informationally-enriched environments, through the manipulation of one of the optical correlates of current displacement velocity.

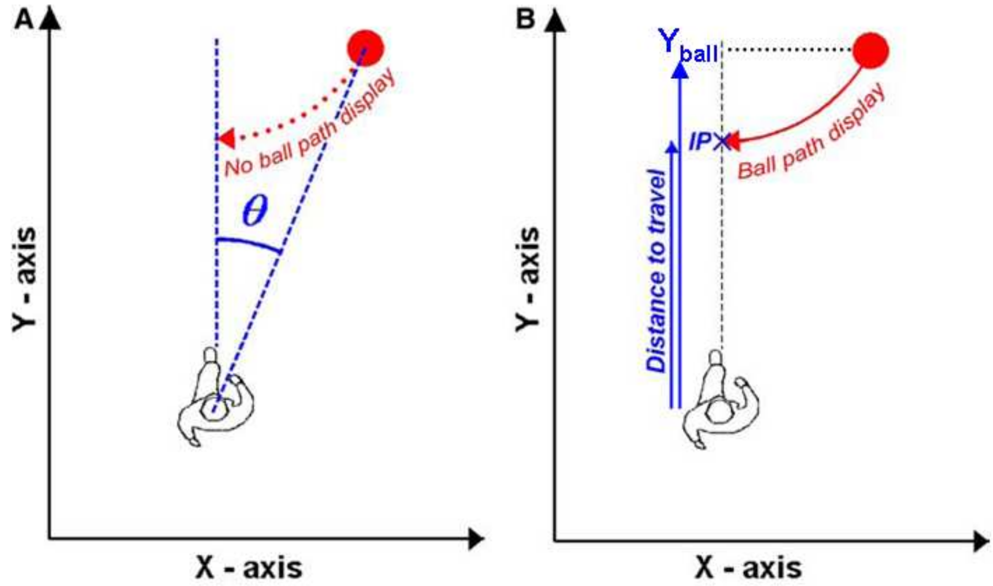

Figure 40 : Schematic sketches of the experimental layout. Participants walked on a rectilinear path and aimed to intercept balls that travelled toward their displacement axis. (A) The natural informative content of the agent-ball environment includes the bearing angle (θ), which forms the informative support of the CBA strategy. The CBA strategy holds that the agent's velocity is regulated so as to cancel change in θ. (B) When the ball track is displayed on the screen, the informative content of the visual scene is enriched according to natural conditions. The distance to the interception point (IP) is part of the informative support of the MRV strategy.

It is now well established that two optical correlates of displacement velocity, Global Optic Flow Rate (GOFR) and Edge rate (ER), are used by participants to judge their displacement velocity (e.g., Larish & Flach, 1990; Warren, 1982) and to control their velocity while performing a perceptual-motor task (e.g., Fajen, 2005b ; François, Morice, Bootsma & Montagne, *under review*). GOFR corresponds to the (average) angular velocity of texture elements in the environment. GOFR is inversely proportional to eye height and independent of texture density. ER corresponds to the number of texture elements that pass by the observation point in a given visual direction. ER is independent of eye height and dependent on texture density. In a recent study, François et al. (under review) (cf., Chapter 2, section 2.2) showed that both GOFR and ER are indeed used by the participants to control walking speed but also that biasing GOFR induced larger modifications of walking velocity than biasing ER. On the basis of this latter result, we decided in the present experiment to bias GOFR while participants attempted to intercept a moving ball in either normal or informationally enriched environments. If the MRV strategy is indeed used in the enriched environment, biasing GOFR (i.e., an optical correlate of displacement speed, cf Equation 2) should affect displacement velocity adjustments. Conversely, the same manipulation should not affect the regulation behavior of participants in the normal environment, as participants would rely on the CBA strategy (cf., Equation 1) that does not depend on the perception of self-motion speed.

METHOD

Participants

Eight male students (mean age 22.75 ± 2.86 years) gave their informed consent before participating in the experiment. They all had normal or corrected-to-normal vision while their experience in ball games varied. A local ethics committee approved the experimental protocol.

Apparatus

The virtual reality set-up (Figure 41A) consisted of two PC Dell workstations (Intel® Core™ 2 CPU 6400 1 Go RAM; Asus GeForce EN8400GS), a treadmill (Medical Development), a video-projector (BARCO IQ R500) and a 2.3 m high × 3.0 m wide projection screen. The participants walked on the treadmill, equipped with a 0.80 m wide × 1.96 m long moving belt that glided over a flat and rigid surface, and wore headphones in order to avoid potential use of auditory information on walking speed emanating from the treadmill. Participants were attached to the back of the treadmill by means of a weight-lifting belt and a rigid rod, which allowed small vertical and sideward movements while participants walked on the treadmill (Figure 41A). 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 by a RS-232 serial port to the first host computer that monitored the velocity of the belt and computed the position of participants in the virtual scene on-line. Virtual positions were sent by a RS-232 serial port to the second host computer in charge of generating the corresponding visual scene. Images were back-projected (refresh rate 60 Hz) onto the screen, positioned 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 × 1.15 m) and a 0.1 m wide red displacement axis

(Figure 41A). The end-to-end latency of the virtual set-up was estimated to be at maximum 30 ms.

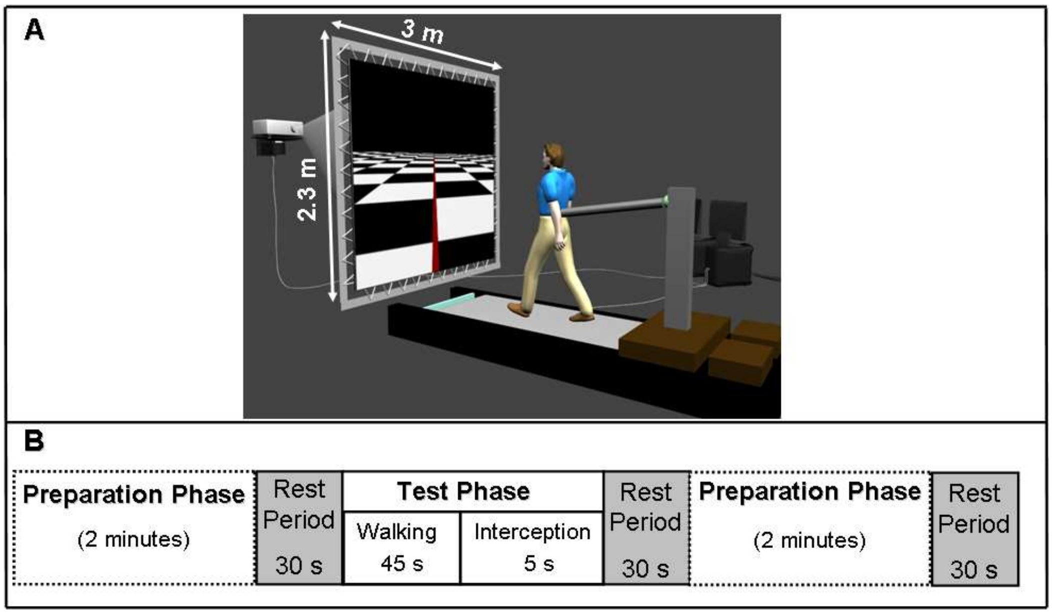

Figure 41 : (A) Overview of the virtual reality set-up and the visual scene that was projected onto the screen in front of the participants; (B) Representation of the different phases of the experiment.

Experimental Procedure

Before beginning the experiment proper, participants were asked to walk 5 minutes on the treadmill in order to familiarize themselves with the apparatus. Participants were then asked to walk as naturally as possible during 3 minutes. Their preferential walking velocity was recorded and both the mean and variability (SD) of displacement velocity computed. We used the experimental protocol developed by François et al. (*under review*) which corresponded to a preparation phase followed by a test phase, separated by a 30 s rest period during which participants stood upright in the dark (Figure 41B).

The inclusion of the preparation phase was essentially methodological. By forcing the participants to adopt several different speeds during the preparation phase, we expected them to rely on the visual information available during the test phase when they had to reproduce their preferred walking speed. During the preparation phase preceding each test phase, participants were asked to walk at an imposed velocity, corresponding to 80%, 100% or 120% of their preferred velocity, during 2 minutes (Figure 41B). To drive the participants to walk at the imposed velocity, a visual feedback was provided by a green or red environment if participants walked, respectively, slower or faster than the prescribed velocity.

The test phase comprised two different tasks. In the first part of the test phase, participants were asked to walk at their preferred walking velocity during 45 seconds (walking task). In the second part of the test phase participants were to intercept a moving ball, appearing on the right hand side of the visual scene, by modifying, if necessary, their displacement velocity (interceptive task). At the end of each interception trial, successful interception was indicated to participants by the appearance of a green square, whereas a miss was indicated by a red square. The ball always approached while moving from right to left, and participants were forced to move forward.

Independent variables

During the test phase, we manipulated the Curvature of the ball path (two modalities), the Display Condition of the ball path (two modalities) and the Eye Height (three modalities).

The balls could approach along a rectilinear path (no curvature condition) or along a curved path (negative curvature conditions) (Figure 42B). In the curved conditions, a constant curvature of $-0.2\ m^{-1}$ was achieved by making the ball move along (a portion of) an imaginary circle with a radius of 5 m, passing through the departure and arrival points of the ball. In half of the trials, the ball-path-displayed condition, the spatial ball path was depicted in the virtual environment throughout the trial duration, as a 0.2 m wide line situated 0.4 m below the ball path (cf., Morice et al., 2010, Chapter §) (Figure 42A). In the remaining trials, the ball-path-not-displayed condition, the ball approached without its path being depicted in the virtual environment. Finally GOFR was manipulated through variations in Eye Height that corresponded either to the participants' veridical eye height (control condition)(EH) or was multiplied (EH 2) or divided (EH 0.5) by a factor 2 (Figure 40A).

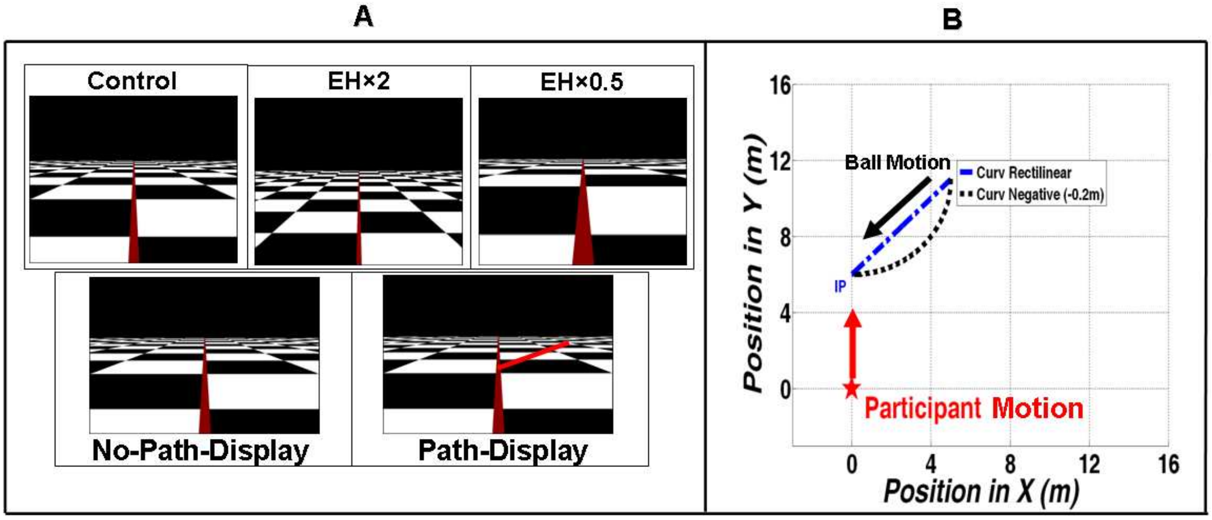

Figure 42: Experimental variables manipulated in this experiment: (A) screenshots presented to participants of the different conditions of Eye Height (upper panels) and Display Conditions (lower panels). Eye height could be veridical (control) multiplied by two (*EH 2)* or divided by two (*EH 0.5)*. Moreover in half of the trials, the trajectory of the ball was displayed (Path-Display) while in the other half of the trials the ball's trajectory was not displayed (No-Path-Display). (B) The balls could approach along a rectilinear path (no curvature condition) or a curvilinear path (negative curvature conditions).

The 36 experimental conditions (3 Preparation Velocities × 3 Eye Heights × 2 Curvatures × 2 Display Conditions) were repeated 3 times each, giving rise to a total of 108 trials per participant. For each of these 108 trials, maintaining the initial velocity unchanged would have allowed the participants to intercept the ball (Offset 0). In order to prevent participants from anticipating the future arrival point of the ball, we randomly interspaced the experimental trials with 24 catch trials with ball offsets corresponding to +2 m or –2m. In the absence of changes in participant walking velocity, the balls would make contact with the head in the 0-m offset condition, pass 2 m in front of the head in the 2-m offset condition, and pass 2 m behind the head in the –2-m offset condition.

Data analysis and dependent variables

The analyses focused on the two tasks of the test phase: the walking task and the interceptive task.

<u>Walking task</u>

The analyses of the walking kinematics were based on the position-time series (sampled at 200 Hz) for each experimental trial of each participant. Position date were filtered using a second-order low-pass Butterworth filter with a cut off frequency of 10 Hz that was ran through twice (in opposite directions) in order to negate the phase shift and differentiated using a three-point central difference technique We averaged the walking velocities every 5 seconds over the last forty seconds of the trial, giving rise to 8 Time Intervals.

Interceptive task

The analyses focused both on the performance and on the walking velocity.

Performance

We used the Success Rate (SR) and the final Constant Error (CE) as descriptors of participant's performance A trial was considered successful when the Euclidian distance between the center of participants' head and the center of the ball was equal or less than 0.30 m at the moment the ball crossed the participants' displacement axis. Constant error was calculated as the average signed distance along the participants' displacement axis between the center of the head and the center of the ball at the moment at the ball crossed the axis of displacement.

Walking velocity

Position time series were again filtered with a cut-off frequency of 10 Hz and differentiated using a three-point central difference technique. The velocity time series were averaged over intervals of 500 ms (corresponding approximately to one step; for a similar methodology, see Warren et al., 2001) giving rise to 10 Time Intervals, with data being synchronized with the moment at which the center of the ball crossed the participant's axis of displacement.

Statistics

Repeated-measures ANOVAs were used to analyze performance (SR and CE) and walking speed. Partial effect sizes were computed (η^2_p) and post-hoc comparisons were conducted using newman-keuls tests. The p value for statistical differences was set at 0.05.

Predictions

Walking task

In accordance with our previous study (François et al., *under review*), manipulating GOFR via Eye Height should give rise specific speed adjustments. More particularly, participants should decrease their walking speed in the case the displacement speed specified by GOFR (EH 0.5) is higher than the actual displacement velocity and *vice versa*.

Interceptive task

Numerical simulations allow several predictions to be made for each strategy (Figure 43). These simulations were based on the average coefficients (k_1 and k_2, cf., Equations 1 and 2) found by Morice et al. (2010) and the bias in perceived velocity found by François et al. (under review). Following the results of Morice et al. (2010), the different display conditions should favor the use of a specific law of control. In the *No-Path-Display* condition the use of a CBA strategy should give rise to distinct displacement velocity profiles for the different curvature conditions. Moreover, Eye Height should influence the displacement velocity profiles moderately; more precisely manipulating eye height should influence essentially the initial conditions (i.e., the participant's velocity when the trial begins). In the *Path-Display* condition the use of a MRV strategy should lead the participants to produce the same velocity profile whatever curvature condition. Conversely, manipulating Eye Height should give rise to clearly distinguishable velocity profiles with a very slow convergence of the curves as compared to the *No-Path-Display* condition. Finally, it is worth noting that the velocity adjustments resulting from the use of a CBA strategy should lead the participant to succeed in the task under all experimental conditions, while the operation of a MRV strategy should lead the participant to fail when Eye Height is increased or decreased, relative to normal, with final errors in the order of +/- 0.8 m.

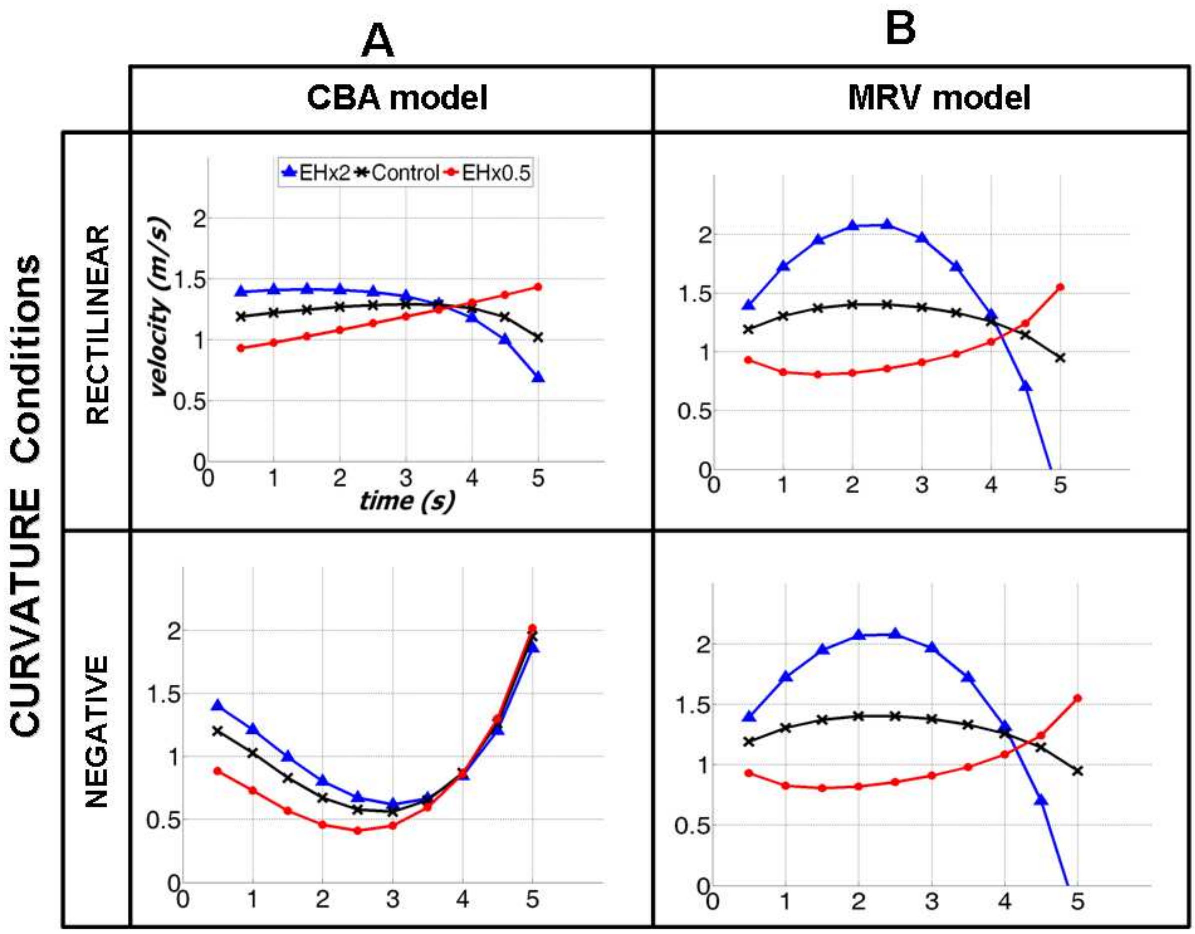

Figure 43 : Numerical simulations of the walking speed provided by the CBA (A) and the MRV (B) models, as a function of ball path Curvature and Eye Height.

RESULTS

Walking task

A three-way repeated measures ANOVA (3 Preparation Velocities × 3 Eye Heights × 8 Time Intervals) with displacement speed as dependent variable revealed significant main effects of Eye Height ($F_{(2,14)}$ = 109.55, $P < 0.05$, $\eta^2_p = 0.94$) and Time Intervals ($F_{(7,49)}$ = 12.60, $P < 0.05$, $\eta^2_p = 0.64$), but no significant effect of Preparation ($F_{(2,14)}$ = 0.30, $P > 0.05$, $\eta^2_p = 0.04$). A *posteriori* comparisons revealed that participants increased their walking velocity (Figure 44) when Eye Height was increased (*EH 2*), in comparison with the *control* condition (EH) (1.30 vs. 1.19 m/s, P < 0.05). Conversely, participants decreased their walking velocity in comparison with the *control* condition when Eye Height was decreased (*EH 0.5*) (0.93 vs. 1.19 m/s, P < 0.05). These results are in agreement with those obtained by François et al. (*under review*); decreasing Eye Height gives rise to an overestimation of walking speed and as a consequence to a slowing down of locomotion pace (and *vice versa*). Moreover, the fact that velocity of walking during the preparation phase does not affect speed adjustments during the test phase led us to remove this factor from the remaining analyses.

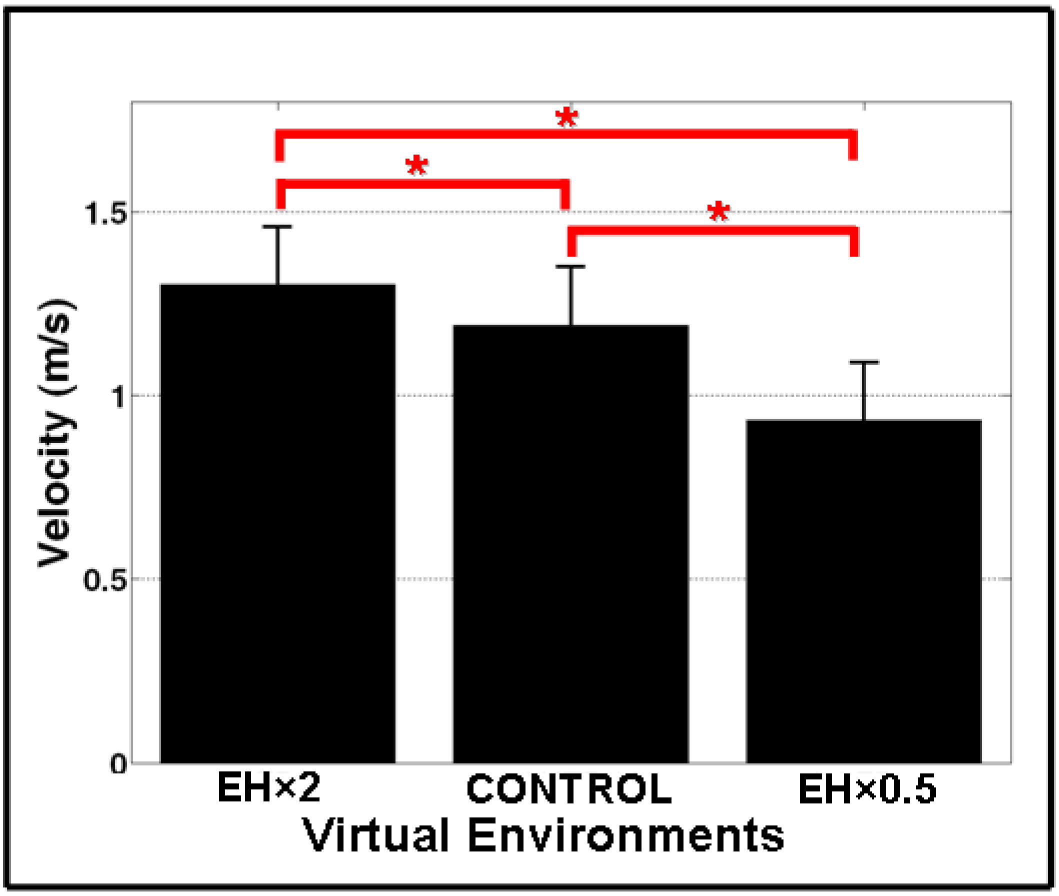

Figure 44 : Average walking velocity during the locomotion task of the test phase as a function of Eye Height conditions. Participants' walking velocity was higher in *EH 2* condition than in the *control* condition. Participants' walking velocity was lower in *EH 0.5* than in the control condition. The errors bars represent between-participant standard deviations.

<u>Interceptive task</u>

Performance

Three-way repeated-measures ANOVAs (3 Eye Heights × 2 Curvatures × 2 Display Conditions) with Success Rate as dependent variable revealed a main significant effect of Display factor ($F_{(1,7)}$ = 15.06, $P < 0.05$, η^2_p = 0.69) (Figure 45A). A posteriori comparisons revealed that participants performed better in the *Path-Display* condition than in the *No-Path-*

Display condition (81.7 vs., 75.5 %, respectively). A three-way repeated-measures ANOVAs (3 Eye Heights × 2 Curvatures × 2 Display Conditions) with Constant Error as dependent variable revealed a main significant effect of Curvature ($F_{(1,7)} = 29.70$, $P < 0.05$, $\eta^2_p = 0.81$) (Figure 45B). A *posteriori* comparisons revealed that participants arrived slightly early at the interception point (negative errors: -0.1 m) with negative curvature and slightly late (positive error: 0.18 m) with rectilinear trajectory.

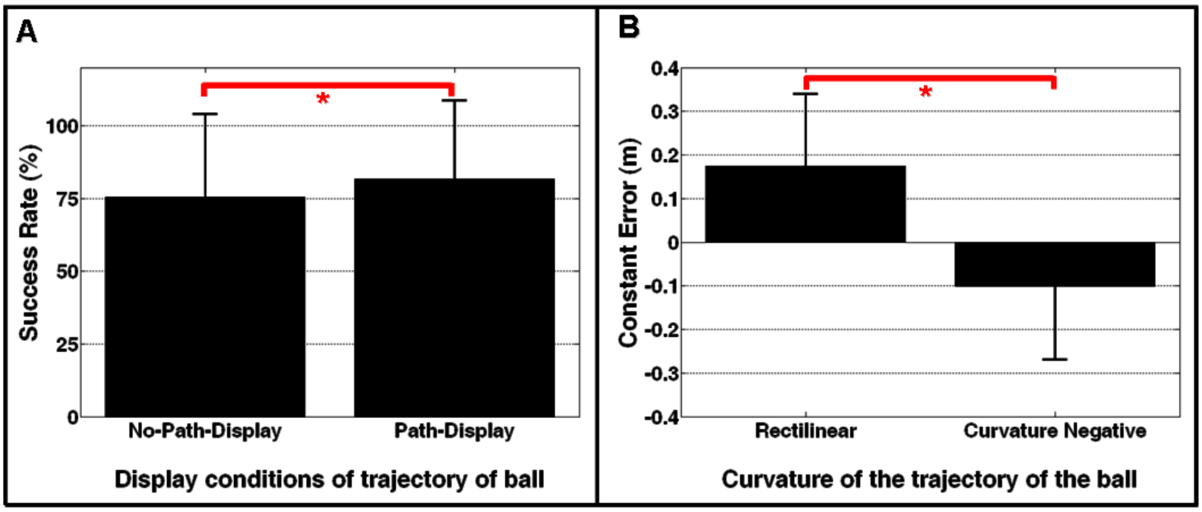

Figure 45 : Average success rate (A) and constant error (B) as a function of ball path display and ball path curvature. (A) Participants performed better in the *Path-Display* condition than in the *No-Path-Display* condition. (B) Participants reached the interception point (negative errors) with negative curvature slightly early and late (positive error) with rectilinear trajectory.

Kinematics

A four-way repeated-measures ANOVA (3 Eye Heights × 2 Curvatures × 2 Display conditions × 10 Time Intervals) with walking speed as dependent variable revealed significant main effects of Eye Height ($F_{(2,14)} = 69.67$, $P < 0.05$, $\eta^2_p = 0.91$) and Curvature ($F_{(1,7)} = 46.65$, $P < 0.05$, $\eta^2_p = 0.87$). We also found significant interactions between Eye Height and Time Intervals ($F_{(18,126)} = 27.92$, $P < 0.05$, $\eta^2_p = 0.79$), Curvature and Time Intervals ($F_{(9,63)} = 116.58$, $P < 0.05$, $\eta^2_p = 0.94$), Display and Time Intervals ($F_{(9,63)} = 22.66$, $P < 0.05$, $\eta^2_p = 0.76$). and Eye Height, Curvature, Display and Time factors ($F_{(18,126)} = 2.14$, $P < 0.05$, $\eta^2_p = 0.23$). Post-hoc analyses performed on this last interaction revealed several important effects. First of all, the time course of walking speed is affected differently by the curvature manipulations depending on the presence (or not) of ball-path display. In the *No-Path-Display* condition (left panels in Figure 46), the *negative* curvature condition gave rise to more pronounced changes in displacement speed than the rectilinear condition. More precisely, the *negative* curvature conditions gave rise to a decrease in displacement velocity in the first part or the trial followed by a pronounced increase in displacement velocity in the second part of the trial (P<.05). Conversely, in the *ball-path display* condition, the reverse picture was observed. The displacement velocity changes were more pronounced in the rectilinear condition in comparison with those produced in the negative curvature condition. In this last condition, an increase in displacement velocity was observed in the first part of the trial, followed by a pronounced decrease in velocity during the second part of the trial (P<.05).

Finally, the marked difference in initial displacement velocity in the three Eye Height, conditions whatever the experimental condition (i.e., Curvature and Display Conditions), indicated that we had succeeded in manipulating an optical correlate of displacement velocity. Interestingly a *posteriori* comparisons indicate a late convergence of the velocity profiles corresponding to the three Eye Height conditions in the *Path-Display* condition in comparison with the *No-Path-Display* condition (red zones in the Figure 46). While the velocity profiles can still be differentiated 3 seconds after the beginning of the trial in the *Path-Display* condition, the convergence appears earlier (after 2 seconds) in the *No-Path-Display* condition (P<.05).

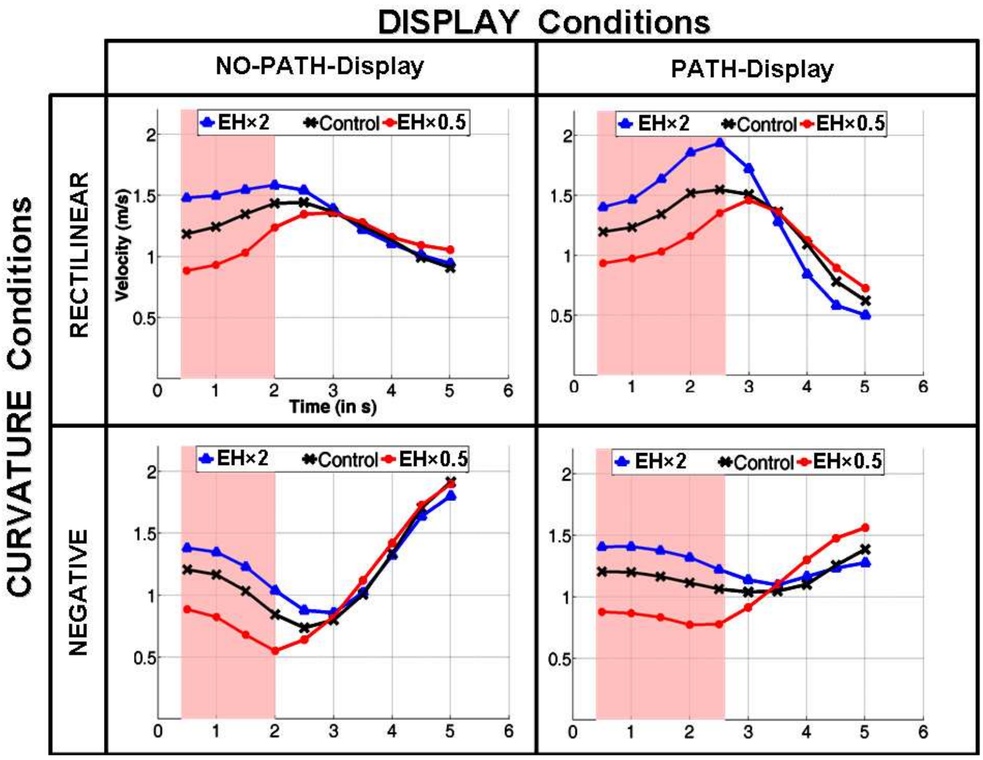

Figure 46 :The time course of the average walking speed produced as a function of the ball-path-Display, the ball path Curvature and the Eye Height (×, ▲ and ● symbols, correspond to veridical Eye Height, Eye Height multiplied by two and Eye Height divided by two, respectively). The red zone represents the time interval during which the velocity profiles can still be differentiated

DISCUSSION

In line with the previous work of Morice et al. (2010) and François et al. (under review), the aim of the present study was to question the operation of the MRV strategy in informationally enriched environments, through the manipulation of one of the constituting component of the strategy, i.e., an optical correlate of current displacement velocity. We asked participants to modify, if necessary, their displacement velocity so as to intercept with their head approaching virtual balls, while ball path curvature, ball path display and eye heights were manipulated. As shown by François et al. (*under review*), manipulating eye height should lead participants to misperceive self-motion speed and as a consequence to fail in the task when a MRV strategy is used to control the action. Moreover, in the case a MRV strategy would be used, ball curvature should not affect the regulation behavior of the participants and the velocity profiles exhibited for each eye height condition should be clearly distinguishable. The results provide mitigated support in favor of these predictions and will be discussed in the following sections.

Walking Task

In agreement with the results obtained by François et al. (*under review*)(see also Fajen, 2005b; Larish & Flach, 1990) manipulating eye height gave rise to specific displacement velocity changes illustrating the functional role played by GOFR in the visual control of locomotion speed. Decreasing eye height gave rise to an overestimation of walking speed (due to an increase of GOFR) and as a consequence to a slowing down of locomotion pace, while the opposite result was obtained in the case of an increase in eye height. This result is important as it demonstrates that we have succeeded in biasing self-motion speed in this experiment; as a consequence, if a MRV strategy is involved in the perceptual control of interceptive tasks, manipulating eye height should give rise to considerable changes at the level of both the overall performance and the displacement kinematics.

Interceptive Task

First of all the overall performance was found to be marginally affected by the display-conditions, with the participants producing a slightly better performance when the ball path was depicted (81.7 % vs., 75.5 %). Remember that in the case the participants would use the MRV (in particular in the ball-display-condition) we expected large errors in the order of +/- 0.8 m. At first sight, this result thus speaks against the operation of the MRV strategy whatever the path-display condition. The results also revealed several displacement velocity adjustments in the different experimental conditions that need to be considered in more detail.

Combined effects of ball path display and curvature on displacement kinematics

In the case a CBA strategy would operate in a normal, unmodified environment (i.e., no-path-display) the ball path curvature should affect displacement kinematics. Our results are in agreement with this prediction, with negative curvature giving rise to an overall decrease in displacement speed in the first part of the trial followed by an overall increase in speed in the second part of the trial. This result is in accordance with a number of recent studies in which ball path curvature was manipulated (e.g., Bastin et al., 2006b, 2008; Morice et al., 2010). When the ball-path is added to the environment a different picture emerges. While the operation of a MRV strategy would have led participants to exhibit the same displacement kinematics whatever ball path curvature, the displacement velocity profiles did differ over the curvature conditions. Even if these differences are smaller in comparison to the no-path-display condition (see also Morice et al., 2010) curvature clearly had an effect on displacement kinematics even when the trajectory is depicted. To conclude this section, while the results of the no-path-display condition unambiguously reflect the operation of a CBA strategy, the results of the path-display condition do not speak in favor of the exclusive use of given perceptual-motor strategy.

Effects of eye height manipulations on displacement kinematics

Manipulating eye height was particularly important in this study as it allowed us to de-correlate one of the constituting components of the MRV strategy. This manipulation was supposed to leave the behavior unaffected in the presence of a normal, unmodified environment but to affect displacement kinematics when ball path was depicted. The regulation behavior was indeed not affected by eye height manipulations in the no-path-display condition. This result strongly supports the operation of the CBA strategy (which is independent of eye height manipulations) in a normal, unmodified environment. Once again, in the path-display condition our results are less clear, even if the velocity profiles can still be differentiated 3 seconds after the beginning of the trial, while the convergence of the velocity curves occur a second sooner in the no-path-display condition. This last result is compatible with the operation (at least at some point) of the MRV strategy when the environment is enriched.

CONCLUSION

Taken together our results clearly demonstrate the operation of a CBA strategy in the presence of a normal, unmodified environment. When ball path is depicted, we would like to advocate the use of a more complex strategy. The use of a pure MRV strategy should have led the participants to largely fail on the task when eye height was manipulated, but also to produce distinct velocity profiles during the overall trial. This last prediction was confirmed at least at the beginning of the trial (first 3 seconds), while the former is not. These results suggest that the participants' relied on a MRV strategy at the beginning of the trials and modified their displacement velocity accordingly up to a moment (around 2 s before head-ball contact) where it became clear that the current strategy would not allow them to succeed the task. The perceived inadequacy between the current regulation behavior and the adjustments required to succeed in the task probably drove the participants to use another strategy. In the end, this unexpected result mirrors once again the flexibility of the perceptual-motor organization underlying the control of goal-directed behavior, in the sense that not only different laws of control can operate depending on the informational content of the environment, but also that different laws of control can operate jointly during the completion of the task to the benefit of the participant. Examining the conditions of this complementarity offers a very challenging perspective for future work.