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RESEARCH ARTICLE

Environmental constraints modify the way an interceptive action is controlled

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Abstract This study concerns the process by which agents select control laws. Participants adjusted their walking speed in a virtual environment in order to intercept approaching targets. Successful interception can be achieved with a constant bearing angle (CBA) strategy that relies on prospective information, or with a modified required velocity (MRV) strategy, which also includes predictive information. We manipulated the curvature of the target paths and the display condition of these paths. The curvature manipulation had large effects on the walking kinematics when the target paths were not displayed (informationally poor display). In contrast, the walking kinematics were less affected by the curvature manipulation when the target paths were displayed (informationally rich display). This indicates that participants used an MRV strategy in the informationally rich display and a CBA strategy in the informationally poor display. Quantitative fits of the respective models confirm this information-driven switch between the use of a strategy that relies on prospective information and a strategy that includes predictive information. We conclude that agents are able of taking advantage of available information by selecting a suitable control law.

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Introduction

During the last few decades, a number of laws of control have been proposed to account for the perceptual control of goal-directed displacements (e.g., Chardenon et al. 2004; Peper et al. 1994; Warren et al. 2001; Wilkie and Wann 2002; see also Fajen 2005a, for a critical review). These laws of control have been shown to account for the behavior of different kinds of agents, including humans, insects, and robots (Duchon and Warren 2002), and also for the regulation of behavior under a wide variety of experimental conditions (Chardenon et al. 2005). Even so, it is probable that agents are able to select different control laws in different situations (e.g., use different control strategies depending on environmental constraints). To give an example, a particular agent might use a different control law for the interception of a fully predicable target movement than for an unpredictable target. We believe that the selection of control laws raises questions that are worthy of being addressed (cf. Lenoir et al. 2005; Schöner and Dose 1992; Warren 1988; Warren and Kay 1997).

One might ask, for instance, how widely a particular control law is applied or if and how task constraints affect which control law has been selected. Such questions arise in everyday situations. Consider a car driver that has to adjust his or her forward motion with respect to approaching vehicles. This might occur when the driver arrives at a roundabout or at an intersection with a bicycle path or an intersection with tramlines. Depending on weather conditions or the height of roadside vegetation, the

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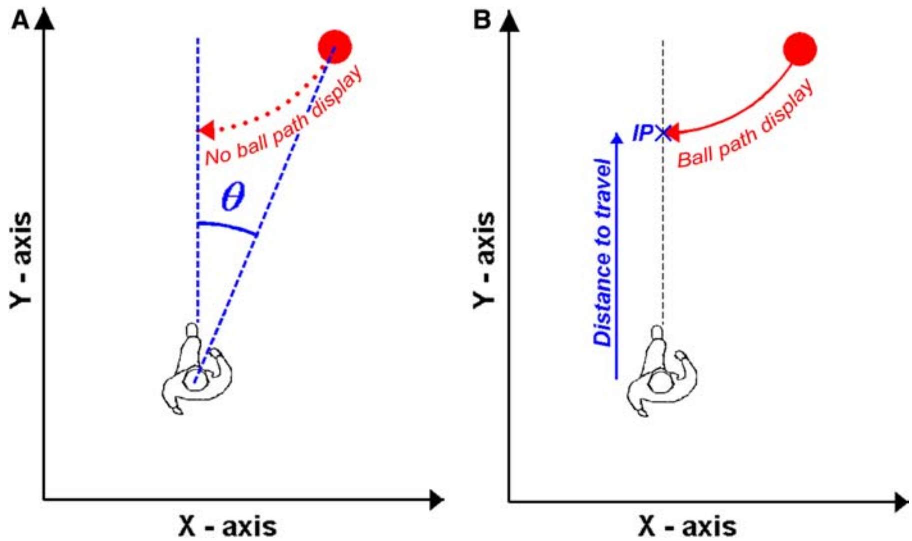

Fig. 1 Schematic sketches of the experimental layout. Participants walked on a rectilinear path and aimed to intercept balls that traveled toward their displacement axis. **a** The natural informational content of the agent-ball environment includes the bearing angle (θ), which forms the informational 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 screen, the informational content of the visual scene is enriched relative to natural conditions. The distance to the interception point (*IP*) is part of the informational support of the MRV strategy

path of the approaching vehicle might or might not be visible. An intersection that is clearly visible under normal weather conditions, for instance, might not be so with snowfall. To what extent does the visibility of the path of the approaching vehicle affect the driver's control of forward motion? Or, more generally, to what extent does the visibility of the path of motion of moving objects affect the control of agents that interact with the objects? To address this type of questions we chose to use the following experimental paradigm.

Participants in our experiment walked on a straight path through a virtual environment and adjusted their walking speed in order to intercept approaching targets. This paradigm is well suited to our purpose because the visibility of the target paths can easily be manipulated and because different perceptual-motor strategies can be used to perform the task. A first candidate control law is the constant bearing angle (CBA) strategy. The bearing angle is the angle subtended by the current position of the target and the direction of displacement of the observer (Fig. 1a). Using a CBA strategy means walking so as to maintain the bearing angle constant, which leads one to intercept the target.[1] The CBA strategy is prospective in the sense that the absence of change in the bearing angle informs participants about the sufficiency of their current regulation. The strategy gives rise to an on-line control of the action independently of the place and time of arrival of the ball (cf. Beek et al. 2003; Michaels and Oudejans 1992; Montagne 2005).

Following Warren et al. (2001) and Wilkie and Wann (2002), the CBA strategy can be modeled with a point-attractor system architecture:

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

In this equation, $\dot{Y}$ is the walking speed (in m/s), $\ddot{Y}$ is the acceleration (in m/s^2), $\dot{\theta}$ is the rate of change of the bearing angle (in deg/s, with $\dot{\theta} > 0$ indicating an increase in θ), k_1 is a parameter that modulates the strength of the coupling between $\ddot{Y}$ and $\dot{\theta}$, and k_2 is a parameter that modulates the strength of the damping term. The parameter vmd is a visuo-motor delay that is estimated to be 100 ms (cf. Zago et al. 2009).[2] The function $\frac{1}{1+200\times e^{-10\times t}}$ is an S-shaped or sigmoid activation function of time t that increases from close to 0 at $t = 0$ to close to 1 at $t = 1$. This function accounts for the time needed by agents to detect the bearing angle and modify their velocity accordingly at the beginning of the trial.

We have previously shown that this apparently simple control strategy accounts for the regulation of participants' walking speed when task constraints are varied within trials

[1] Other prospective strategies are possible if the visual environment contains a structured background. For instance, moving so as to keep the same distant object occluded by the target would also lead to the interception of the target.

[2] Additional simulations were performed that used delays of up to 0.2 s. These simulations led to reasonably similar predictions. The same was true for the model described in Equations 2 and 3. We speculate that the precise value of the delay is not crucial in this task because the implied variables change fairly slowly as compared to in faster interception tasks such as catching.

(Chardenon et al. 2005) and between trials (Bastin et al. 2006a), and also when the informational content of the visual scene is impoverished (Bastin and Montagne 2005) or biased (Bastin et al. 2008). The visual environments (non-stereo images) that were used in these previous studies consisted of a textured ground plane and the ball to be intercepted and, as such, provided few alternatives to the use of the CBA strategy. In the current experiment, we present additional information, which allows participants to use other control strategies, and hence allows us to study if and how individuals select among the different candidate strategies.

In the framework of predictive strategies, both place and time of arrival of the ball act as input variables. As an example, pre-programmed interceptive movements might be triggered when predictive information reaches a threshold value (Tresilian 2005; Tydesley and Whiting 1975). Such strategies are likely to be used only in a limited range of interceptive tasks, for instance when the movement time is very short and/or when a moving target is intercepted indirectly (e.g., Benguigui et al. 2003; Smith et al. 2001). Given that the effectiveness of predictive strategies depends on the accuracy of the initial predictions, any information that would allow observers to better discriminate the time and place of arrival of the ball should be expected to facilitate the operation of this type of strategies. To our knowledge, however, no purely predictive strategies have been proposed for the interception of moving targets on foot, which should not lead one to discard the possibility that predictive information is used as part of an on-line regulation process (cf., Desmurget and Grafton 2000; Starkes et al. 2002).

As an alternative to purely prospective and purely predictive control strategies, hybrid strategies might involve information-based control architectures that resemble prospective ones but that include predictive information. An example of a hybrid strategy is the required velocity model considered in this study (Fig. 1b; cf. Bastin et al. 2008). This model is related to the required velocity model for hand movements (Peper et al. 1994; cf. Bootsma et al. 1997; Jacobs and Michaels 2006). The model holds that

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

and that

$$\dot{Y}_{\text{req}}(t) = (Y_{\text{IP}} - Y(t))/\text{TTC}(t), \qquad (3)$$

in which Y, $\dot{Y}$, and $\ddot{Y}$ are the participant's position, speed, and acceleration. The parameter vmd is the visuo-motor delay (100 ms), $\dot{Y}_{\text{req}}$ is the required walking speed, Y_{IP} is the future interception position, and *TTC* is the time remaining before the ball reaches Y_{IP}. Finally, k_1 and k_2 are constants.

Equation 2 holds that participants accelerate according to a difference between the actual and required velocities; at this level the strategy is prospective in the sense that participants are informed about the sufficiency of the current regulations. Predictive information is embedded in Eq. 3 in the form of time-to-contact information and information concerning the future interception point. With the inclusion of predictive information the model differs from other required velocity models. In fact, required velocity models were introduced to provide an alternative to the use of predictive information (Peper et al. 1994). To acknowledge this difference, we refer to Eqs. 2 and 3 as a modified required velocity (MRV) model.[3]

To summarize, the control laws considered in this study are a strategy that relies on prospective information (the CBA strategy) and a strategy that also includes predictive information (the MRV strategy). The CBA strategy can be classified as a prospective control law and the MRV strategy as a hybrid (prospective-predictive) control law. The issue addressed in the study concerns the possible influence of environmental constraints on the type of strategy used to intercept moving targets on foot. As described below, the environmental constraints that we manipulate concern the informational content of the visual scene.

The selection of different laws of control according to the visual content of a scene has previously been addressed by Lenoir et al. (2005), who asked volleyball players to intercept volleyballs that approached them on straight or curved trajectories. The curved trajectories were accompanied by spin of the balls, which was more visible for colored balls than for white balls. The players exhibited displacement reversals for curved trajectories, despite the fact that the initial position of the players coincided with the place of arrival of the ball (see Montagne et al. 1999, for a similar effect in one-handed catching). These reversals indicate the operation of a prospective type of control in which players maintain a lateral alignment with the ball. Interestingly, the reversals were less pronounced when colored balls were used, which is to say, when local predictive information related to spin was available. These results provide a first indication that environmental constraints (in this case local information available on the ball itself) can affect the type of control law that is selected to perform interceptive actions.

The present study further investigates and extends such findings using a task that requires whole-body displacements. More precisely, we test the robustness of the CBA strategy in the presence of strong spatial information. Participants walked along a straight trajectory through a

[3] We tested several versions of the MRV model. However, the additional simulations did not lead to better overall fits than Equations 2 and 3. The results of the additional simulations are therefore not reported.

virtual environment and they were asked to adjust their walking speed in order to intercept moving targets. In previous experiments, the curvature of the ball path has been shown to influence the participants' displacements as predicted by the CBA strategy (Bastin et al. 2006a). In the present experiment, we manipulated both the curvature of the ball path and the display condition of the ball path (look ahead to Fig. 3b). Displaying the ball path consisted of presenting the track followed by the ball, from the starting position of the ball to the place of contact, as a white stripe through the virtual environment. In the condition in which the ball path was displayed, predictive information about the ball path curvature and the place of arrival of the ball was made explicit. This additional information allows participants to use several control laws, and hence allows us to study if and how, depending on the informational content of the environment, participants select among the different candidate control laws.

Method

Participants

Eleven male and two female students (mean age 25 ± 2 years) gave their informed consent before participating in the experiment. They all had normal or corrected-to-normal vision, and their experience with ball games varied. A local ethics committee approved the experimental protocol.

Apparatus

A general overview of the experimental set-up is presented in Fig. 2. The set-up comprised a treadmill (Gymrol, BRL 1800), a large projection screen (2.3-m height × 3.0-m wide), a video projector (BARCO IQ R500), and two computers (cf., Bastin et al. 2006a; Rugy et al. 2000). Participants walked on the treadmill, equipped with a 0.6-m wide × 1.80-m long moving belt that glided 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, which allowed small vertical and sideward movements while participants walked on the treadmill. The projection screen was positioned in front of participants, at a distance of 0.70 m, providing a 118° × 130° field of view. The velocity of the treadmill was sampled via an optical encoder (200 Hz) and sent by a RS-232 serial communication to a PC workstation that used this velocity to generate the movement of the visual scene. The visual scene was projected onto the screen by a video-projector at an update rate of 60 frames/s. The visual scene consisted of a textured ground plane (bricks), a 0.1-m wide brown displacement axis, and a spherical, moving, red target with a physical diameter of 0.22 m and an optical size that naturally expanded during the approaches. The spatiotemporal performance of the virtual environment is estimated to allow the visual consequences of a change in walking speed to be displayed within a maximum delay of 30 ms.

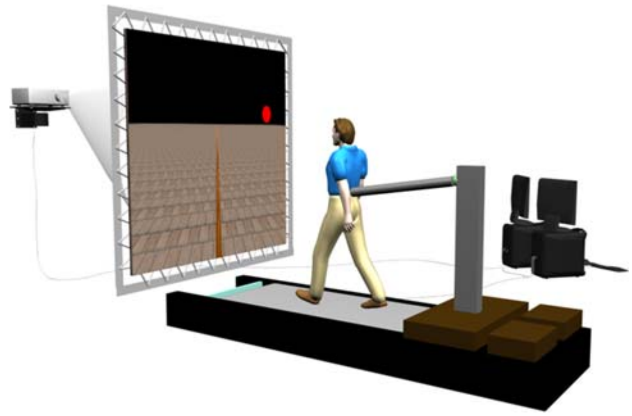

Fig. 2 Overview of the virtual reality set-up and the visual scene that was projected onto the screen in front of participants

Experimental procedure

Before the experimental session, the initial velocity of the moving belt was individually adjusted until participants reported a subjective feeling of an easy walking pattern. The participant's eye height with regard to the screen was also customized before the experiment. Once the participant stood on the treadmill, we measured his or her eye height and used this measure to compute the visual scene. At the start of each trial, participants were required to stabilize their walking speed between 1.15 and 1.25 m/s. To do so, a visual gauge was displayed on the projection screen, consisting of a vertical white line of 0.3 m representing the current velocity and a rectangular zone representing a velocity interval centered on 1.2 m/s. To satisfy the initial task requirements, the line had to be kept within the prescribed rectangular zone. When the prescribed velocity was maintained for 500 ms, the gauge disappeared and the trial began. The balls, which moved at eye height, had to be intercepted at the moment at which they crossed the displacement axis. To achieve this, participants regulated their walking speed, when deemed necessary, so as to be at the interception point at the right time (5 s after the balls appeared). Qualitative visual feedback was given: a green square was displayed at the end of successful trials and a red square at the end of unsuccessful trials. A trial was considered successful if the distance between the centers of the virtual ball and the participant's head was less than 0.3 m at the moment at which the ball reached the interception point.

Independent variables

We manipulated the ball offset (three modalities), the curvature of the ball path (three modalities), and the display condition of the ball path (two modalities). The three offset conditions (i.e., different starting positions of the ball) were used in order to change the position at which the balls crossed the displacement axis (see Fig. 3a). These positions were computed on the basis of the initial walking speed (1.2 m/s). In the absence of accelerations or decelerations, 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. The reason for manipulating the offset was to force participants to produce different displacement regulations and to prevent them from locating the place of arrival of the balls too easily.

As also shown in Fig. 3a, the balls approached along a rectilinear path (no curvature condition) or a curvilinear path (positive and negative curvature conditions; cf. Bastin et al. 2006a). In the curvilinear 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 ball path was depicted in the virtual environment (see Fig. 3b). This was achieved by displaying a 0.2-m wide stripe 0.4 m below the ball path throughout the trial duration. Preliminary tests had indicated that such a stripe allows participants to better discriminate ball path characteristics (i.e., curvature and place of arrival). Positioning the stripe on the floor was found to be less effective. In the remaining trials, the ball-path-not-displayed condition, the ball approached without its path being depicted in the virtual environment.

The 18 experimental conditions (2 display conditions × 3 offsets × 3 curvatures) were repeated 5 times each, giving rise to a total of 90 trials that were presented in a random order. A 5-min rest was given after 45 trials. Before the experiment, participants performed 36 training trials. Two repetitions of the 18 experimental conditions were used in the training session. The whole experiment lasted approximately 1 h.

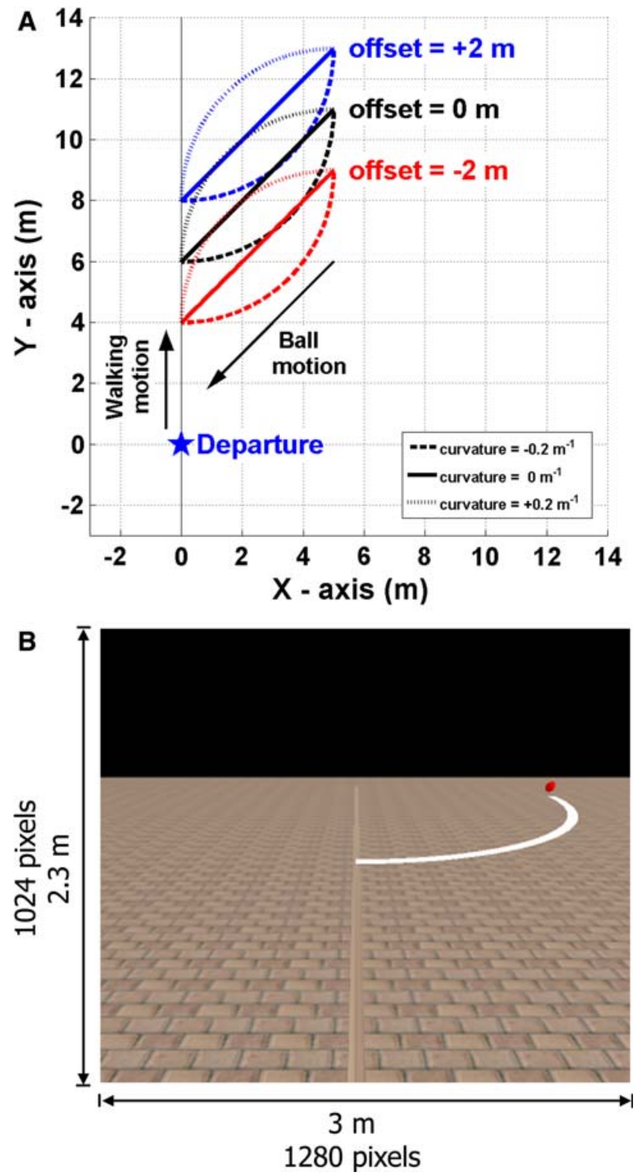

Fig. 3 **a** Bird's eye view of the displacement axis and the different ball trajectories. Participants' displacements were constrained along the *Y*-axis. The ball followed a rectilinear path (curvature = 0 m^{-1}) or one of two curvilinear paths (curvature = −0.2 and +0.2 m^{-1}). The *X*-coordinate of the starting position of the ball was always 5 m. The *Y*-coordinate of this position was 9, 11, and 13 m, for the −2, 0, and +2 m offset conditions, respectively. The *Y*-coordinate of the interception point was 4, 6, and 8 m, for the −2, 0, and +2 m offset conditions. **b** The visual scene and the display of the ball track as seen from the perspective of participants. The display consisted of a white stripe positioned 0.40 m below the path followed by the ball

Data analysis and dependent variables

The analyses focused on performance, on the walking kinematics, and on the explanatory value of the candidate perceptual-motor strategies.

Performance

We used success rate (SR) and final spatial error or constant error (CE) to assess participants' performance. SR was computed in two different ways. A trial was deemed successful if the Euclidian distance between the center of the head and the center of the ball was reduced to less than 0.3 m (1) at the moment at which the ball crossed the axis of displacement (i.e., 5 s after the ball appearance) or (2) at any moment during the trial. SR was calculated as the percentage of successful trials relative to the total number of trials. The CE was calculated as the average signed distance along the *Y*-axis between the center of the head and the center of the ball at the moment at which the ball crossed the axis of displacement.

Kinematics

The analyses of the walking kinematics were based on the position-time series (sampled at 200 Hz) for each experimental trial of each participant. We used a forward and backward second order low-pass Butterworth filter with a cut off frequency of 10 Hz. The time series were averaged over intervals of 500 ms (corresponding approximately to one step; for a similar methodology, see Bastin et al. 2006a, and Warren et al. 2001), with data being synchronized at the moment at which the center of the target crossed the participant's axis of displacement. The main analyses focused on how participants modified their walking speed in the different experimental conditions.

Additional analyses were performed to ensure that the observed kinematics reflected on-line regulations and not pre-programmed responses to the different target distances. To achieve this, we computed the within-subjects variability in walking speed and current error for each interval of 500 ms. The current error is the theoretical error that would be observed at the interception point in the absence of further accelerations and decelerations. An increase in walking-speed variability indicates on-line regulations of walking speed, and a concomitant convergence of the current error towards zero implies that the observed regulations were adaptive (Chardenon et al. 2002; Montagne et al. 2003; Camachon et al. 2004).

Perceptual-motor strategy

Two types of analyses were performed to test which perceptual-motor strategy was involved. First, to reveal the possible operation of a CBA strategy, we examined the time course of the bearing angle (see also Bastin et al. 2006a). A bearing angle that remains approximately constant during the course of a trial would be in agreement with a CBA strategy. Likewise, to reveal the possible operation of an MRV strategy, we examined the time course of the difference between the required behavior to succeed in the task and the current behavior ($\dot{Y} \times \mathrm{TTC} - [Y - Y_{\mathrm{IP}}]$; look back to Eq. 3). These analyses are similar to the ones used by Peper et al. (1994) and Montagne et al. (1999).

Subsequent analyses compared the observed and predicted kinematics. The observed kinematics (walking speeds) were averaged for each experimental condition of each participant, hence removing the intra-participant variability over the five repetitions of the trials. The predicted kinematics were obtained by numerically solving Eqs. 1 and 2. The best-fitting parameters (the k_1s and k_2s of the respective models) were determined for each model and each participant, using the same parameters for the different experimental conditions. For the CBA model, k_1 and k_2 were varied from -0.1 to -0.01 in increments of 0.01; for the MRV model these parameters varied from 0.1 to 2 in increments of 0.2. Hence, 100 combinations of parameter values were used for both models. The predictions of the models and the observed data were compared with the sum of squares error (SSE), using the complete trajectories with the exception of the last 0.5 s.[4]

Statistics

Repeated measures ANOVAs were used to analyze performance (SR and CE), walking speed, and the robustness of the perceptual-motor strategies (SSE). Partial effect sizes were computed (η_{p}^2) and post hoc comparisons were conducted using HSD Tukey tests. The *p* value for statistical differences was set at 0.05. All 90 trials (successful and unsuccessful) were used in the analyses.

Predictions

The considered MRV model is based, among other things, on the place of arrival of the ball. Because the place of arrival is the same for different curvatures of ball path, the MRV model predicts that the curvature manipulations do not affect the participants' behavior. On the other hand, the bearing angle is affected by the trajectory curvature and, hence, the CBA strategy does predict effects of curvature manipulations. These effects are most clearly illustrated in the 0-m offset condition, in which no changes in walking speed are required to intercept the ball. In this condition, when the trajectory curvature is positive, a constant walking speed gives rise to a decrease in bearing angle (and thus to a negative rate of change). The use of a CBA strategy therefore predicts an initial increase in walking speed. Such an increase would result in an increase in bearing angle in the second part of the trial, and as a consequence to a decrease in walking speed in the later part of the trial. The predictions of the CBA strategy for a negative curvature are the opposite of those for a positive curvature. With regard to the display of the ball path, we expect that the ball-path-displayed condition facilitates the perception of the place of arrival of the ball. Since the place of arrival serves as input to the MRV model, we expect that the MRV model might be used more frequently in the ball-

[4] We did not use the final .5 s of the trajectories because the walking speed changes predicted by the CBA model are unrealistic for very near targets, especially in the -2 m offset condition.

path-displayed condition than in the ball-path-not-displayed condition. Relating this to the previous arguments, an interaction between the curvature and display manipulations is predicted. Namely, the effect of curvature is predicted to be more pronounced in the not-displayed condition because the MRV strategy might be used less frequently in that condition.

Results

Performance

Figure 4a presents the SRs, computed in two ways. We first considered SR computed with trials in which the Euclidian distance between the agent and the ball was reduced to less than 0.3 m at the moment at which the ball crossed the participant's displacement axis (plain bars). This criterion indicated that participants intercepted the balls in 58% of the trials, on average. They achieved better interception scores in the ball-path-displayed condition than in the not-displayed condition (71 vs. 45%), and also in the rectilinear and negative curvature conditions as compared to the positive curvature condition (71 and 71% vs. 32%). In experiments reported by Bastin et al. (2006a, b) and by Diaz et al. (2009), however, negative curvatures led to less accurate performance than positive curvatures. To analyze this apparent difference with our results we also computed SR with the trials in which the distance between the agent and the ball was reduced to less than 0.3 m during the overall trial course (dotted bars). This analysis revealed that interceptions occurred in more than 90% of the trials.

A two-way repeated measures ANOVA (2 display conditions × 3 curvatures) with SR (computed with the latter definition) as dependent variable revealed significant main effects of display condition ($F_{(1,12)} = 20.69$, $p < 0.05$, $\eta_p^2 = 0.63$) and curvature ($F_{(2,24)} = 10.60$, $p < 0.05$, $\eta_p^2 = 0.47$) but no significant interaction ($F_{(2,24)} = 3.10$, $p > 0.05$, $\eta_p^2 = 0.21$). A posteriori comparisons revealed that participants performed better in the ball-path-displayed condition than in the not-displayed condition (94 vs. 86%), and also in the rectilinear and positive curvature conditions as compared to the negative curvature condition (94 and 95% vs. 81%). The larger number of misses observed in the negative curvature condition is probably due to the fact that this measure accepts as successful interceptions that could have occurred up to 0.30, 0.42 and 1.76 m behind the point at which the ball crossed the displacement axis, for negative, rectilinear and positive curvatures, respectively. This means that the interception window is smaller in the negative curvature condition than in the other curvature conditions (see Fig. 5).

Figure 4b presents the CEs. A two-way repeated measures ANOVA (2 display conditions × 3 curvatures) on the CEs revealed a significant main effect of curvature ($F_{(2,76)} = 66.61$, $p < 0.05$, $\eta_p^2 = 0.64$) and a significant interaction ($F_{(2,76)} = 19.15$, $p < 0.05$, $\eta_p^2 = 0.34$). The CEs confirm that participants took advantage of the spatial interception windows. Indeed, a posteriori comparison revealed that the CE in the positive curvature condition was different from the errors for the other curvatures; with positive curvatures, participants arrived early at the interception point (negative errors), whereas they arrived slightly late at the interception point in the other curvature conditions (positive errors). The interaction indicates that the effect of curvature was more pronounced when the ball path was not depicted on screen.

Kinematics

Figure 6 presents the average walking speeds for the different experimental conditions. The same pattern of results is apparent for the different offset conditions. Let us first consider the condition without a visible ball path (upper

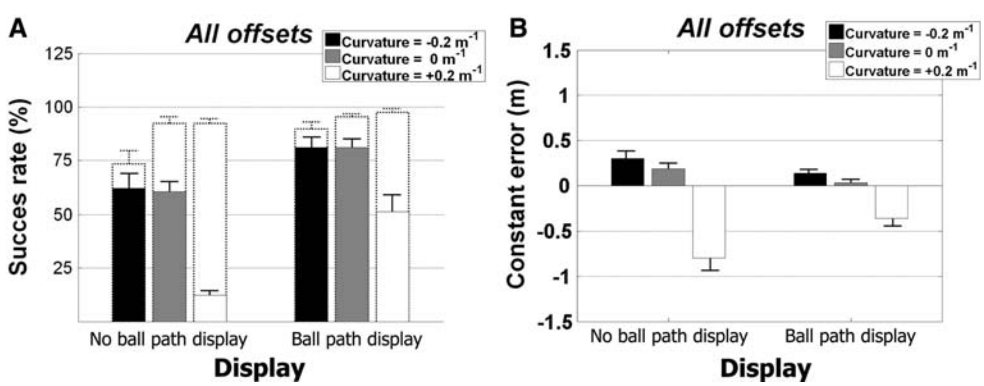

Fig. 4 Average success rate (*SR*) (**a**) and constant error (*CE*) (**b**) as a function of ball path curvature and ball path display. Two computations of SR are displayed in (**a**). The *plain bars* depict the SR computed from the agent-ball distance at time $t = 5$ (s). The additional *dotted bars* represent the SR computed from the minimum of the agent-ball distance across the overall time-course of the trial. *Vertical bars* depict the standard error of the individual means

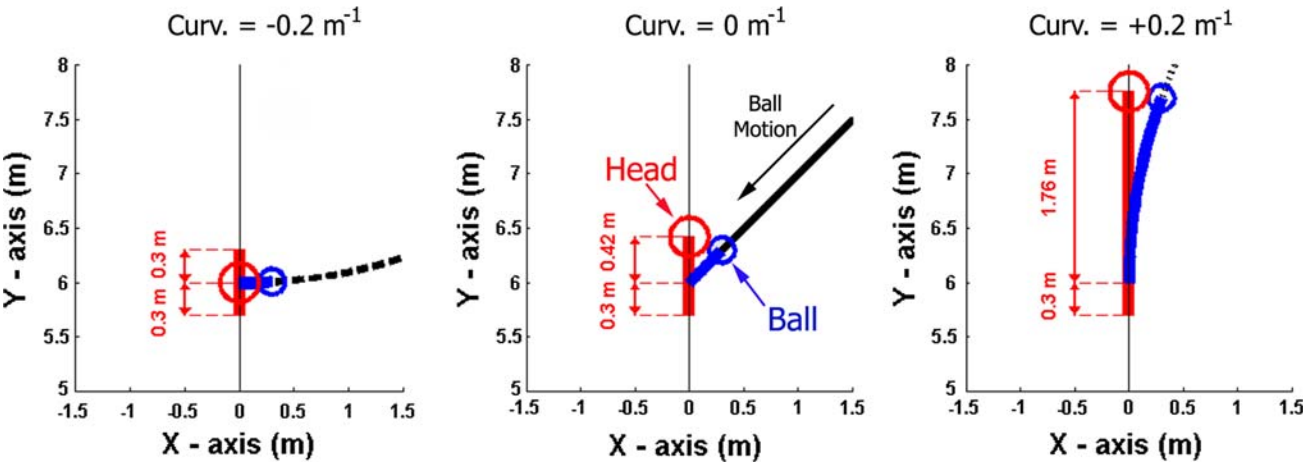

Fig. 5 Interception windows for negative, rectilinear and positive curvatures. The parts of the ball trajectories and the participant's locations from which the ball can be intercepted are indicated with *thick blue* and *red lines.* Interception could occur 0.30 m before the point at which the ball crossed the displacement axis and up to 0.30, 0.42 and 1.76 m behind this point, for negative, rectilinear and positive curvatures, respectively

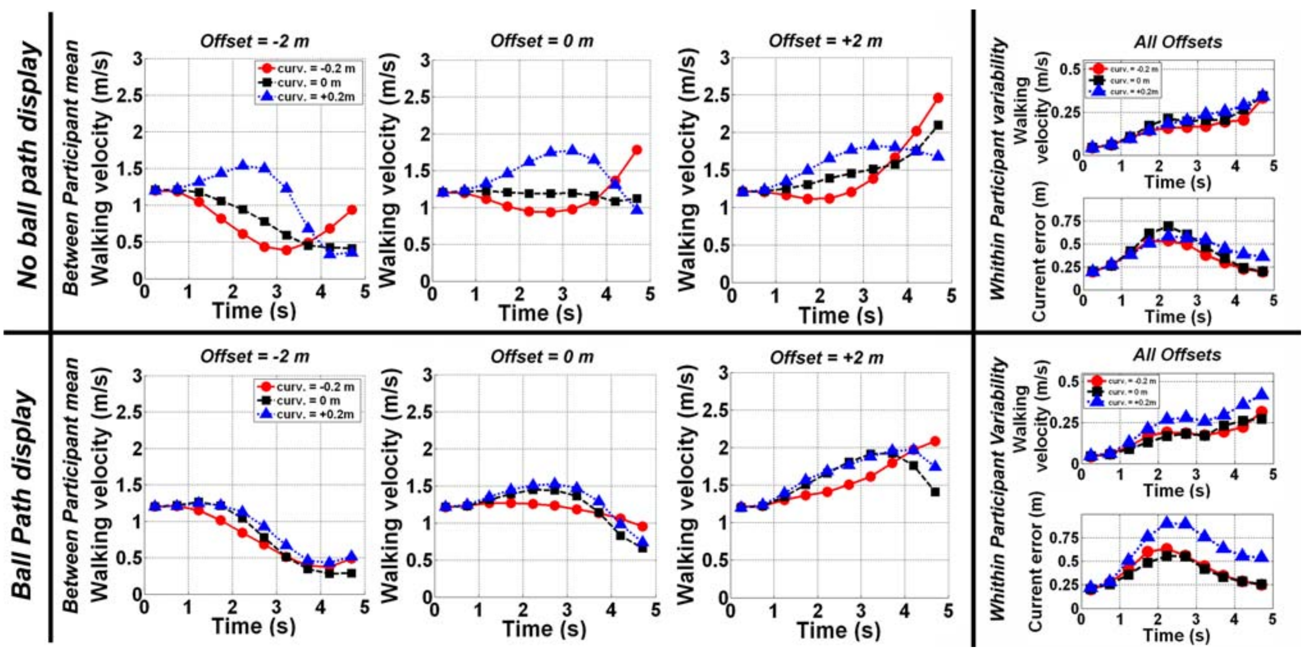

Fig. 6 The time course of the average walking speed as a function of the target offset, the ball path display, and the ball path curvature (*filled circles* symbols depict the negative, *filled triangle* symbols the rectilinear, and *filled square* symbols the positive curvature conditions). The *right column* shows the within participant variability of walking speed and current error averaged for all target offsets as a function of curvature

panels). In the first part of the trials, the walking speeds in the positive curvature condition (filled triangle symbols) are higher than the walking speeds in the rectilinear condition (filled square symbols) which, in turn, are higher than the walking speeds in the negative curvature condition (filled circle symbols). Opposite effects can be observed in the final part of the trials. In the condition with a visible ball path (lower panels), the differences between the curves are less pronounced. Hence, the curvature manipulations seemed to have a larger effect in the absence of the visible path.

To test these effects we performed a three-way repeated measures ANOVA (2 display conditions $\times$ 3 curvatures $\times$ 10 time intervals) with walking speed as dependent variable for each offset condition. Let us describe the results for the 0-m offset condition. This analysis revealed

Table 1 Results of the ANOVAs performed on the walking-speed profiles for each offset condition (−2, 0 and +2 m)

Effect	Offset = −2 m		Offset = 0 m		Offset = +2 m	
	ANOVA	η_p^2	ANOVA	η_p^2	ANOVA	η_p^2
Ball-path-display	$F_{(1,12)} = 10.40$*	0.57	$F_{(1,12)} = 12.63$*	0.51	$F_{(1,12)} = 30.68$*	0.72
Curvature	$F_{(2,24)} = 77.76$*	0.77	$F_{(2,24)} = 44.32$*	0.79	$F_{(2,24)} = 5.88$*	0.33
Time interval	$F_{(9,108)} = 76.20$*	0.33	$F_{(9,108)} = 6.30$*	0.34	$F_{(9,108)} = 63.96$*	0.84
Ball-path-display × time interval	$F_{(9,108)} = 2.75$*	0.64	$F_{(9,108)} = 16.92$*	0.58	$F_{(9,108)} = 9.74$*	0.03
Ball-path-display × curvature	$F_{(2,24)} = 26.19$*	0.59	$F_{(2,24)} = 23.07$*	0.66	$F_{(2,24)} = 0.32$*	0.05
Curvature × time interval	$F_{(18,216)} = 40.30$*	0.64	$F_{(18,216)} = 20.20$*	0.63	$F_{(18,216)} = 20.21$*	0.63
Ball-path-display × curvature × time interval	$F_{(18,216)} = 21.51$*	0.46	$F_{(18,216)} = 9.96$*	0.45	$F_{(18,216)} = 8.75$*	0.42

* $p < 0.05$

significant main effects of display condition ($F_{(1,12)} = 12.63$, $p < 0.05$, $\eta_p^2 = 0.51$), curvature ($F_{(2,24)} = 44.32$, $p < 0.05$, $\eta_p^2 = 0.79$), and time interval ($F_{(9,108)} = 6.30$, $p < 0.05$, $\eta_p^2 = 0.34$). We also found significant interactions between display condition and time interval ($F_{(9,108)} = 16.92$, $p < 0.05$, $\eta_p^2 = 0.58$), display condition and curvature ($F_{(2,24)} = 23.07$, $p < 0.05$, $\eta_p^2 = 0.66$), curvature and time interval ($F_{(18,216)} = 20.20$, $p < 0.05$, $\eta_p^2 = 0.63$), and between display condition, curvature, and time interval ($F_{(18,216)} = 9.96$, $p < 0.05$, $\eta_p^2 = 0.45$). Most interestingly, post hoc analyses performed on this last interaction revealed that the time course of walking speed was affected differently by the curvature manipulations depending on the presence (or not) of a ball-path display. The statistical results for the other offset conditions were similar (see Table 1). Overall, the ANOVAs confirmed the trends previously observed in Fig. 6.

The differences between the speed profiles in the absence of a ball-path display are consistent with the operation of a CBA strategy, and the reduction of the differences between the speed profiles in the presence of a visible ball path indicates the operation of a strategy that relies on the place of arrival of the ball, such as an MRV strategy that includes predictive information. The predictive values of the CBA and MRV strategies are addressed in-detail in the next section. However, we first consider the within-participants variability in walking speed and current error (Fig. 6, right column). The figure shows a gradual increase in walking-speed variability in the two display conditions. The current error variability increases until 2.5 s and then decreases until interception. As expected, this variability pattern suggests functional regulations of walking speed due to on-line perception–action corrections. Note that these variability patterns of walking velocity and current error occurred even when the ball path was visible, hence ruling out the possibility that participants used a purely open-loop strategy also in this condition.

Perceptual-motor strategy

Figure 7 presents the time course of a quantity related to the MRV model (upper panels) and of the bearing angle (lower panels), for one representative participant. The quantity related to the MRV model (look back to Eq. 3) converges toward zero earlier and more in the ball-path-displayed condition (right panel, on top) than in the condition without the path display (left panel, on top), indicating the operation of an MRV strategy only in the presence of a visible ball path. The time course of the bearing angle is plotted along with the time course of the bearing angles that would have occurred if participants had maintained a constant walking speed, assuming that they adopted the speed that would lead them to intercept the balls. Without a visible ball path, the observed bearing angles deviate from the hypothesized constant speed bearing angles well before the end of the trials, and the deviations are in the direction of keeping the bearing angle constant. Such adaptations are less pronounced or even absent in the condition in which the path is displayed. This is consistent with the operation of a CBA strategy in the presence of a visible ball path.

Figure 8 illustrates the walking kinematics for the entire group of participants, along with the numerical simulations of the candidate models, for the 0-m offset condition. The gray area in the figures is the area between the average walking speed plus and minus one standard deviation. The best-fitting predictions of the CBA and MRV models are represented by the dotted and solid curves, respectively. Overall, the dotted curves (CBA) seem to approximate the gray area better than the solid curves (MRV) in the ball-path-not-displayed condition (upper panels), whereas the solid curves approximate the gray area better in the ball-path-displayed condition (lower panels). Hence, the CBA strategy seems to be of better explanation of the walking kinematics in the condition without visible ball path, whereas the MRV strategy seems to be of better explanation in the condition with a visible ball path.

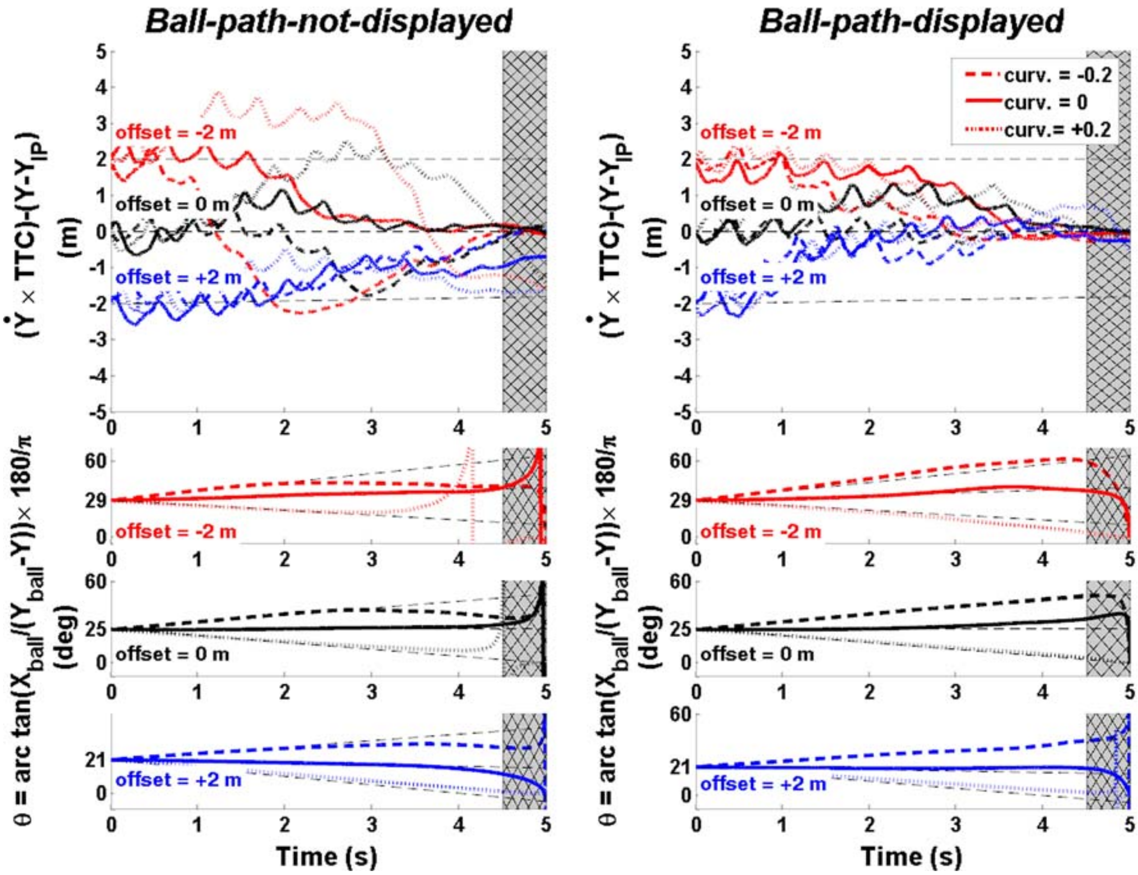

Fig. 7 The raw-data time course, for a representative participant, of the quantity $\dot{Y} \times \mathrm{TTC} - (Y - Y_{\mathrm{IP}})$ and of the bearing angle as a function of target path curvature, target offset, and ball path display (*left panel*, *ball-path-not-displayed* condition; *right panel*, *ball-path-displayed* condition). *Top panels* display the quantity $\dot{Y} \times \mathrm{TTC} - (Y - Y_{\mathrm{IP}})$ which represents the difference between the distance that would be traveled if the participant would maintain the current velocity unchanged until contact and the current distance from the participant to the interception point. Higher frequency components correspond to increases and decreases of the walking speed due to footsteps. *Lower panels* depict the time course of the recorded bearing angle that is plotted along with the time course of the theoretical bearing angles (*straight lines*) that would have occurred in the absence of changes in the optimal velocity required to intercept the ball (0.8, 1.2 and 1.6 m/s for the offset −2, 0 and +2 m, respectively). The hatched *gray area* depicts the last 0.5 s of the trials, in which bearing angle display chaotic changes for near targets

To test these results, a two-way repeated measures ANOVA (2 display conditions × 2 Models) was performed on the SSE values obtained by fitting the two models to the observed kinematics. The ANOVA revealed a significant main effect of display condition ($F_{(1,12)} = 8.63$, $p < 0.05$, $\eta_p^2 = 0.37$), a significant main effect of model ($F_{(1,12)} = 7.18$, $p < 0.05$, $\eta_p^2 = 0.42$), and a significant interaction ($F_{(1,12)} = 34.81$, $p < 0.05$, $\eta_p^2 = 0.74$). The interaction is illustrated in Fig. 9. Post hoc tests revealed that whereas the errors for the CBA model were smaller in the ball-path-not-displayed condition than in the ball-path-displayed condition (0.77 vs. 1.57 m^2/s^2), the opposite was true for the MRV model (1.19 vs. 0.70 m^2/s^2). This confirms the trends previously illustrated in Figs. 7 and 8. The SSE values of the individual participants and the best-fitting parameters are presented in Table 2.

Discussion

The aim of this study was to determine to what extent environmental constraints affect the selection of control strategies. More precisely, we set out to study whether the informational content of a visual scene affects which control law is selected by participants who control their forward walking speed in order to intercept approaching targets. We manipulated the curvature and display conditions of the ball trajectories. On the basis of previous research, it was hypothesized that perceivers would use a strategy that relies upon prospective information (the CBA strategy) in the absence of a ball-path display. It was further hypothesized that displaying the ball trajectories would allow participants to integrate predictive spatial information as predicted by an MRV control law.

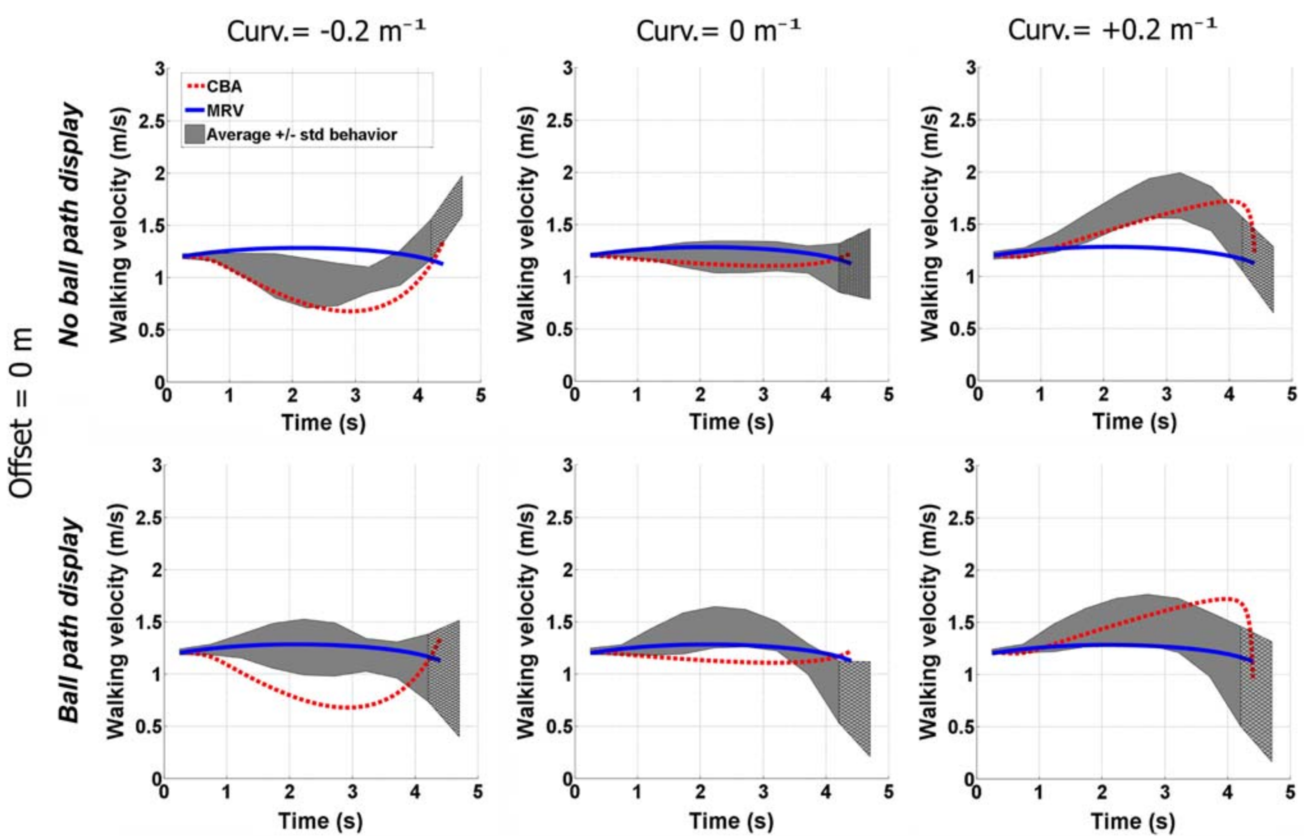

Fig. 8 Average observed walking speeds for the entire group of participants ($n = 13$) and the best-fitting numerical simulations of the average observed walking speed provided by the CBA and MRV models, as a function of ball path curvature and display condition, for the 0 m offset condition. The upper and lower bounds of the *gray* area are the average observed walking speed ± one standard deviation. The *hatched part* of this area depicts the last 0.5 s of the trials, which was not used for the simulations. CBA numerical simulations are depicted with a *dotted line* and MRV simulations with a *solid line*

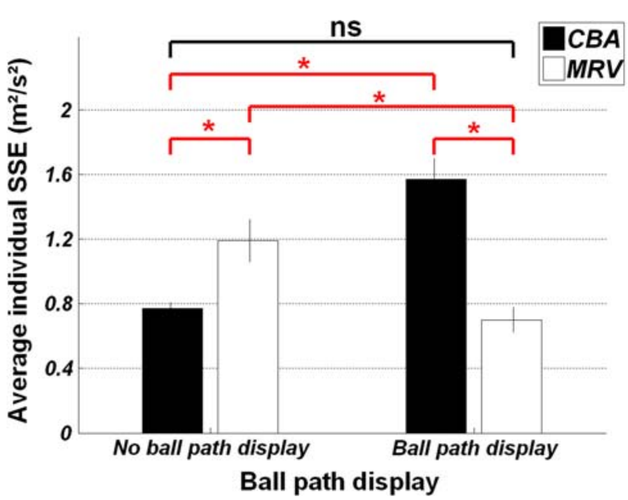

Fig. 9 Average individual values ($n = 13$) of the sum of squares error (*SSE*) obtained from comparisons between individual walking-speed profiles and the numerical simulation of the CBA and MRV models for the different display conditions. The *vertical bars* depict the standard errors of individual means. *Asterisk* indicates statistical difference (post hoc Tukey's HSD test, $p < 0.05$), whereas "*ns*" indicates the absence of a statistical difference ($p > 0.05$)

CBA versus MRV strategies

In the absence of a ball-path display, differences in the curvature of the target trajectory give rise to differences in the walking-speed profiles. This indicates the operation of a CBA strategy. For example, in the 0-m offset condition, in which a constant speed is sufficient for interception, a positive curvature goes together with a decrease in bearing angle and a corresponding increase in walking speed. This increase in walking speed gives rise to an increase in bearing angle in the second part of the trial, which is accompanied by a decrease in walking speed close to target contact. Also in the absence of a path display, negative curvatures were found to have the opposite effect on the walking speeds, again as predicted by the CBA strategy.

This support for the CBA strategy is consistent with previous results (e.g., Bastin et al. 2006a, 2008). The main interest of our study, however, lies in the condition with the display of the target path. In this condition, the velocity profiles obtained for different curvatures are more difficult to distinguish. If we focus on the 0-m offset condition, the

Table 2 Sum of squares error (SSE, in m^2/s^2) expressing the quantitative fit of CBA and MRV models to the observed kinematics and the average best-fitting parameters for each model in the two display conditions for each participant ($n = 13$)

Display	Participants	Laws of control					
		CBA			MRV		
		SSE	k_1	k_2	SSE	k_1	k_2
No ball path display	1	0.97 ± 1.38	−0.05	−0.03	1.13 ± 0.96	0.90	1.30
	2	0.81 ± 1.2	−0.05	−0.04	1.1 ± 0.73	1.10	1.30
	3	0.67 ± 0.88	−0.05	−0.03	0.74 ± 0.33	0.70	1.10
	4	0.78 ± 1.18	−0.06	−0.03	1.36 ± 1.16	0.90	1.30
	5	0.91 ± 1.08	−0.04	−0.04	0.4 ± 0.33	0.50	1.10
	6	0.55 ± 0.63	−0.06	−0.03	1.02 ± 0.79	0.90	1.30
	7	0.79 ± 1.21	−0.03	−0.03	1.06 ± 0.82	1.10	1.30
	8	0.81 ± 1.05	−0.03	−0.03	0.83 ± 0.72	1.10	1.10
	9	0.56 ± 0.6	−0.06	−0.02	2.22 ± 1.77	1.10	1.50
	10	0.72 ± 0.69	−0.07	−0.03	1.57 ± 1.54	1.10	1.30
	11	0.84 ± 0.74	−0.06	−0.03	1.25 ± 0.97	0.90	1.30
	12	0.97 ± 1.54	−0.05	−0.03	0.97 ± 0.8	0.90	1.30
	13	0.62 ± 0.76	−0.08	−0.05	1.78 ± 1.49	1.10	0.90
	Mean	0.77	−0.05	−0.03	1.19	0.95	1.24
	Std	0.14	0.01	0.01	0.47	0.19	0.15
Ball path display	1	1.73 ± 1.85	−0.05	−0.03	0.68 ± 0.43	0.90	1.30
	2	1.49 ± 1.52	−0.05	−0.04	0.51 ± 0.48	1.10	1.30
	3	0.64 ± 0.83	−0.05	−0.03	0.84 ± 0.54	0.70	1.10
	4	1.71 ± 1.15	−0.06	−0.03	0.57 ± 0.28	0.90	1.30
	5	1.09 ± 1.09	−0.04	−0.04	0.18 ± 0.1	0.50	1.10
	6	1.57 ± 1.14	−0.06	−0.03	1.01 ± 0.73	0.90	1.30
	7	1.63 ± 1.44	−0.03	−0.03	0.82 ± 0.62	1.10	1.30
	8	1.22 ± 1.32	−0.03	−0.03	0.46 ± 0.35	1.10	1.10
	9	2.17 ± 1.34	−0.06	−0.02	1.3 ± 1.1	1.10	1.50
	10	2.51 ± 1.38	−0.07	−0.03	0.74 ± 0.38	1.10	1.30
	11	1.5 ± 1.56	−0.06	−0.03	0.89 ± 0.91	0.90	1.30
	12	1.61 ± 1.72	−0.05	−0.03	0.5 ± 0.42	0.90	1.30
	13	1.59 ± 2.72	−0.08	−0.05	0.58 ± 0.59	1.10	0.90
	Mean	1.57	−0.05	−0.03	0.70	0.95	1.24
	Std	0.46	0.01	0.01	0.28	0.19	0.15

velocity profiles obtained in the negative curvature condition are still slightly different from the other ones, but the speed modifications do not match the predictions of the CBA strategy anymore. Rather, the results seem to call for the operation of a strategy based (at least partly) on predictive information.

These findings are confirmed by the quantitative fits between the candidate models and the observed speed modifications. In the absence of a path display, the CBA strategy provides a better account of the speed modifications than the MRV model. In contrast, in the presence of the display, the MRV model provides a better account of the kinematics. Hence, assuming that our laboratory results generalize to more natural environments, we conclude that observers use different control laws in different situations.

Optical correlates for the MRV model

The formulation of the MRV strategy presented in Eqs. 2 and 3 is based on physical variables. Obviously, the strategy is viable only if perceptual correlates of these variables exist. Let us address this question before we discuss our results in a broader context. The issue related to the perception of the speed of rectilinear self-motion ($\dot{Y}$ in Eq. 2) is well documented. Several optical variables including global optic flow rate (GOFR) and edge rate (ER) have been shown to be useful in this regard; it has been argued that these optical variables are used simultaneously for the perception of self-motion (Larish and Flach 1990) and the control of goal-directed actions (Fajen 2005b). Hence, even though the relative contribution of each variable seems to depend on the task at hand, there is evidence in favor of the use of GOFR and ER.

The required velocity ($\dot{Y}_{\mathrm{req}}$ in Eqs. 2 and 3) is a composite variable that includes the current distance to the interception point and the time remaining before the ball reaches the interception point. Several candidate variables can be considered as information about distance. The height of the interception point in visual field might appear to be one of them (e.g., Ooi et al. 2001). The ball path, however, was displayed as a stripe just below the ball (i.e., above the ground plane), which means that the use of this optical variable would have led to an overestimation of the current distance. Even so, it remains possible that the practice trials allowed participants to adapt to this discrepancy between the actual and specified distance. Alternatively, participants might have used variables in the changing optic flow that specify the distance to objects (not necessarily on the ground surface) in units of eye-height or stride length (e.g., Eqs. 2 and 4 in Warren 2007; cf. Lee 1974). Distance in units of stride length, for example, is specified by the ratio of the *tau*-value of the object to the duration of a stride.

A final optical specification that is necessary for the MRV strategy to be viable is the specification of time to contact. This issue is not trivial among other reasons because *tau* (Lee and Reddish 1981; cf. Bootsma and Oudejans 1993) does not provide reliable estimates of time to contact for approaches on curved trajectories, as in the present study. Nevertheless, Kerzel et al. (2001) showed that participants are able to accurately judge time to contact even in the case of curved trajectories. In their study, the judgments of participants seemed to be based on optical velocity changes. Altogether, the perceptual support for the physical quantities involved in the MRV strategy indeed seems to exist. Further experiments are required to test the optical basis of the strategy.

Efficiency, flexibility, and lawfulness

Why would perceivers select a strategy that involves predictive information in the presence of the ball path display? After all, one of the main advantages of the prospective CBA strategy is that it remains available independently of environmental constraints; as soon as the ball is visible, the strategy can be used (Bastin and Montagne 2005). One might hypothesize that the use of a strategy that involves predictive information (the MRV strategy) is due to an efficiency principle. Even though the CBA strategy allows perceivers to get to the right place at the right time, in some cases it gives rise to unnecessary adaptations in walking speed. Such unnecessary adaptations are illustrated by the effects of curvature in the 0-m offset condition, in which the targets can also be intercepted without any changes in walking speed. The MRV strategy minimizes unnecessary adaptations.

However, in the absence of sufficiently precise predictive information, or if the predictive information is difficult to detect, the use of strategies that involve predictive information might involve larger risks. In such circumstances, errors in the detection of predictive information might lead to unsatisfactory performance. In the condition without a path display, which was less informationally rich, participants appeared to avoid these errors by the use of the prospective strategy. In short, participants in our experiment showed the capacity to select the type of control that takes advantage of the information that happens to be available in the visual scene, while maintaining high levels of performance throughout the experiment.

A number of recent studies provide further evidence for this apparent plasticity of the perceptual-motor organization. For example, various studies have shown how the combination of several (redundant) perceptual variables within a single law of control provides a robust and adaptive control mechanism (e.g., Bastin et al. 2006b; Bruggeman et al. 2007; Warren et al. 2001; Wilkie and Wann 2003, 2005). Our results reveal that this flexibility also occurs at the level of the laws of control; several control strategies take part in the perceptual-motor organization. Given the flexible organization of perception–action systems, then, a major challenge for scientists becomes to discover lawfulness in this flexibility.

Conclusions

Although the CBA and MRV strategies provided reasonably good fits, part of the observed changes in walking speed could not be explained. Let us briefly consider three possible ways in which the predictions might be improved. First, the individual control laws might be optimized, similar to the way in which we modified the original RV model (Peper et al. 1994). Second, the considered control laws could be merged into a higher-order architecture that depends on one or more additional parameters (Warren et al. 2001). This would be equivalent to creating a continuous space and each point of which represents a control law. Selecting a control law then means selecting a locus in the control-law space (the action-equivalent of the notion of information space; e.g., Jacobs et al. 2009). A third possibility can be found in the suggestion that agents regulate their movement to achieve optical states (i.e., a constant bearing angle) at some point in the future (Diaz et al. 2009), perhaps with less predictable environments leading to temporally nearer control and more predictable environments to more temporally distant control.

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