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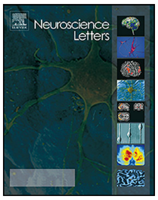

Is perception of self-motion speed a necessary condition for intercepting a moving target while walking?

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HIGHLIGHTS

- Perceiving self-motion velocity is not a *sine qua non*-condition for interception.
- This study illustrates the flexibility of the perceptual-motor strategies involved.
- The role of Global Optic Flow Rate depends on the informational context.

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ABSTRACT

While it has been shown that the Global Optic Flow Rate (GOFR) is used in the control of self-motion speed, this study examined its relevance in the control of interceptive actions while walking. We asked participants to intercept approaching targets by adjusting their walking speed in a virtual environment, and predicted that the influence of the GOFR depended on their interception strategy. Indeed, unlike the Constant Bearing Angle (CBA), the Modified Required Velocity (MRV) strategy relies on the perception of self-displacement speed. On the other hand, the CBA strategy involves specific speed adjustments depending on the curvature of the target's trajectory, whereas the MRV does not. We hypothesized that one strategy is selected among the two depending on the informational content of the environment. We thus manipulated the curvature and display of the target's trajectory, and the relationship between physical walking speed and the GOFR (through eye height manipulations). Our results showed that when the target trajectory was not displayed, walking speed profiles were affected by curvature manipulations. Otherwise, walking speed profiles were less affected by curvature manipulations and were affected by the GOFR manipulations. Taken together, these results show that the use of the GOFR for intercepting a moving target while walking depends on the informational content of the environment. Finally we discuss the complementary roles of these two perceptual-motor strategies.

1. Introduction

Control laws reflect the operation of perceptual-motor principles and allow agents to perform a given task under a wide variety of conditions. Morice et al. [1] questioned the robustness of the Constant Bearing Angle (CBA) control law for the control of interceptive tasks performed by humans. This study showed that the CBA strategy accounted for the speed profiles of agents who intercepted approaching targets under changing task and environmental constraints. According to this law [1,2], maintaining constant the bearing angle subtended by the current position of the target and the direction of the displacement of the observer (Fig. 1A) leads to the interception of the target (Eq. (1)):

$$\ddot{Y} = \frac{1}{1 + 200 \times e^{-10t}} \times k_1 \times \dot{\theta} + k_2 \times \dot{Y} \tag{1}$$

where $\ddot{Y}$ is the walking acceleration (m/s^2). $\dot{Y}$ the walking speed (m/s), $\dot{\theta}$ the rate of change of the bearing angle (°/s), k_1 and k_2 parameters modulating the strength of the coupling between $\ddot{Y}$ and $\dot{\theta}$ and modulating the strength of the damping term, respectively. $1/(1+200 \times e^{-10\times t})$ is an activation function.

However, Morice et al. [1] evidenced that participants did not always rely on the CBA strategy. The study also evaluated the effects of displaying the future trajectory of the target. The CBA strategy predicts that manipulation of the curvature of the target trajectory should have a specific influence on speed adjustments. On the other

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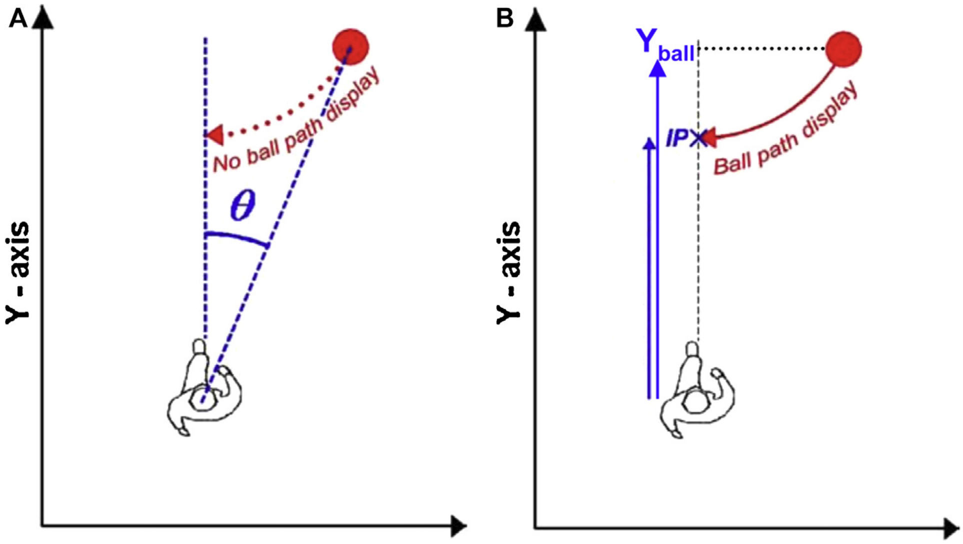

Fig. 1. Schema of the experimental layout. Participants walked on a rectilinear path toward balls that traveled toward their displacement axis. (A) The natural informational content of the agent–ball environment includes the bearing angle (θ), which forms the informational support for the CBA strategy. (B) When the ball track is displayed onscreen, 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 for the MRV strategy.

hand, displaying the future trajectory of the target should not affect how agents regulate their behavior as it does not affect the rate of change in bearing angle. Their results supported the idea that the CBA strategy was used when the future trajectory was not shown, as manipulating the curvature did influence speed adjustments as predicted. In contrast, when the target trajectory was shown, curvature manipulations had less of an influence on walking speed. Moreover, under these conditions a Modified Required Velocity (MRV) strategy (Eqs. (2) and (3)) provided a better explanation of how behavior is regulated than the CBA strategy. According to the MRV strategy [1], agents should accelerate at a rate that depends on the difference between the physical and the required speed:

$$\ddot{Y} = k_1 \times (k_2 \times \dot{Y}_{req} - \dot{Y}) \tag{2}$$

$$\dot{Y}_{req} = \frac{Y_{IP} - Y}{TTC} \tag{3}$$

where Y, $\dot{Y}$, and $\ddot{Y}$ are the agent's physical position, speed, and acceleration respectively, $\dot{Y}_{req}$ the required walking speed, Y_{IP} the future interception position, TTC the time remaining before the target reaches Y_{IP}, and k_1 and k_2 constants (Fig. 1B).

The Morice et al. study [1] therefore identified the boundary conditions in which the CBA strategy operates, and its results are compatible with an information-driven switch between two control laws. Because the MRV strategy (unlike the CBA strategy) takes into account the agent's perception of their walking speed (Eq. (2)), a more direct and elegant test of the MRV strategy is to manipulate the optical correlates of self-motion speed.

It is now well-established that agents use the Global Optic Flow Rate (GOFR) to judge their displacement [3,4] and control their speed while performing a perceptual-motor task [5,6]. The GOFR corresponds to the (average) angular speed of texture elements in the environment. It is inversely proportional to eye height and independent of texture density. François et al. [6] confirmed that biasing the GOFR led to large changes in walking speed. Nevertheless, the question remains as to whether the perception of self-displacement is used to control walking speed in a task in which the primary goal is to intercept a moving target, rather than maintain a constant speed (e.g., preferred walking speed).

In our experiment we biased the GOFR while participants attempted to intercept a moving ball. If it is the case that the MRV strategy is used in enriched environments, biasing the GOFR (i.e., optical correlate of $\dot{Y}$ in Eq. (2)) should result in specific speed profiles. Conversely, in the normal environment this manipulation should not affect how participants regulate their behavior, as they are expected to rely on the CBA strategy (cf., Eq. (1)), which does not depend on the perception of self-motion speed.

2. Materials and methods

2.1. 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. A local ethics committee approved the experimental protocol.

2.2. Apparatus

The virtual reality set-up (Fig. 2A) consisted of two host computers, a treadmill, a video projector, and a 3.0 m wide × 2.3 m high projection screen. Participants walked on the treadmill, equipped with a 0.80 wide × 1.96 long moving belt sliding over a flat and rigid surface. They wore earmuffs in order to prevent them from

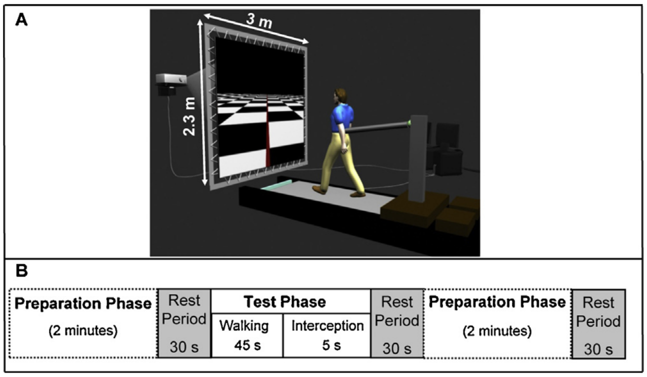

Fig. 2. (A) Overview of the virtual reality set-up and the visual scene that was projected onto the screen in front of participants; (B) experimental phases.

using auditory information from the treadmill to regulate their walking speed. The speed of the treadmill belt was sampled via an optical encoder and sent to the first host computer, which calculated on-line the position of the participant in the virtual scene. Their virtual position was sent by 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 participant (providing a130° × 117° field of view). The scene consisted of a textured ground plane made up of black and white squares (1.15 m wide/high) and a 0.1 m wide red displacement axis.

2.3. Experimental procedure

Before beginning the experiment, participants were asked to walk for 5 min on the treadmill in order to familiarize themselves with the apparatus. Next, they were asked to walk as naturally as possible for 3 min to record their preferred walking speed and compute its mean and standard deviation.

We used the experimental protocol developed by François et al. [6]. This involves a preparation phase followed by a test phase, separated by a 30 s rest period during which participants stand upright in the dark (Fig. 2B). During the preparation phase, participants were asked to walk for 2 min at a set speed that corresponded to 80, 100 or 120% of their preferred speed. In order to help them do this they were given visual feedback. When they walked too slowly, the virtual environment was colored green, and when they walked too fast, it was colored red. By forcing participants to walk at several different speeds, this preparation phase was designed to expect participants to rely on visual rather than proprioceptive information when they had to reproduce their preferred walking speed in the test phase.

The test phase comprised two tasks. In the first (walking task), participants were asked to walk at their preferred speed for 45 s. In the second (interceptive task), participants had to intercept a moving ball that appeared on the right-hand side of their visual field, by modifying, if necessary, their displacement speed.

2.4. Independent variables

We manipulated in the test phase the Curvature of the ball's trajectory (two modalities), the Display of the ball's trajectory (two modalities) and the Eye Height (three modalities).

Curvature. The ball could approach along a rectilinear (No-Curvature) or curved (Negative-Curvature) trajectory. In the curved condition, a constant curvature of −0.2 m was achieved by making the ball travel along (a portion of) an imaginary circle with a radius of 5 m, passing through its departure and arrival points.

Display. Half of the trials were run using the Path-Display condition. In this case, throughout the trial the ball was shown in the virtual environment as a 0.2 m wide line situated 0.4 m below its trajectory (cf., [1]). In the remaining trials (the No-Path-Display condition) the ball's trajectory was not shown.

Eye Height. Finally the GOFR was manipulated through variations in Eye Height that corresponded to the participant's physical eye height (EH, the control condition), or was multiplied by a factor of two (EH×2) or divided by a factor of two (EH×0.5).

The 36 experimental conditions (3 Preparation speed × 2 Curvature × 2 Display × 3 Eye Height) were each repeated three times, making a total of 108 trials per participant.

If the participant's initial speed remained unchanged in each trial, they would be able to intercept the ball (the 0-m offset condition). In order to prevent participants to anticipate the future arrival point of the ball by learning the interception distance during the No-Path-Display condition in which the arrival point was not visible, we randomly interspaced the experimental trials with 24 other trials in which ball offsets corresponded to ±2 m. This should force participants to adapt their walking speed on-line, otherwise, the ball would make contact with the participant's head in the 0-m offset condition; the ball would pass 2 m in front of (behind) their head in the +2-m (−2-m) offset condition.

2.5. Dependent variables

Walking task. Walking speed analyses were based on the position-time series (sampled at 200 Hz) monitored during each experimental trial of each participant of the test phase. Position data were filtered using a 2nd order low-pass Butterworth filter with a cut-off frequency of 10 Hz that was ran through twice (in opposite directions). We took the average walking speed every 5 s over the last 40 s of the trial, which led to eight Time Intervals. This averaging interval was designed to access to an involuntary drift of the participant going against the instructions.

Interceptive task. The analyses focused both on performance and walking speed recorded during the test phase: (i) Performance was measured using the Success Rate (SR) and the final Constant Error (CE). A trial was considered successful when the Euclidian distance between the center of participant's head and ball was equal to or less than 0.30 m at the moment the ball crossed the participant's displacement axis. Constant Error was calculated as the average signed distance along the participants' displacement axis between the centers of their head and ball at the moment the ball crossed the axis of displacement. (ii) To measure walking speed, the position-time series were filtered with a cut-off frequency of 10 Hz and differentiated using a three-point central difference technique. The speed-time series were averaged over 500 ms intervals (approximate duration of a step [6]), which led to 10 Time Intervals.

2.6. Predictions

Walking task. Our earlier work [6] suggested that manipulating Eye Height would give rise to a decrease of walking speed when the displacement speed specified by the EH (EH×0.5) is higher than the actual displacement speed (and vice versa).

Interceptive task. Each of the two display conditions should favor the use of a specific law of control. In the No-Path-Display condition, the CBA strategy should lead to distinct speed profiles for each curvature condition. Moreover, as the optical correlates of self-motion speed do not play a part in the CBA strategy, Eye Height should not influence speed profiles. Therefore, while participants should exhibit different speed profiles depending on the curvature condition, they should succeed in the task. In the Path-Display condition, the MRV strategy should lead to the same speed profile for each curvature condition (as the key parameter is the position of the interception point). Conversely, Eye Height manipulations should lead to distinct speed profiles. More precisely, Eye Height manipulations (i.e., EH×2 and EH×0.5) should lead participants to misperceive their current speed and, consequently, systematically fail with predicted constant errors of up to ±0.8 m.

3. Results

Repeated measures ANOVAs on all manipulations were carried out to analyze performance (SR and CE) and walking speed. Partial effect sizes were computed ($\eta 2p$) and post hoc comparisons were conducted using Newman–Keuls tests such as to minimize type-I errors. The p value for statistical differences was set at 0.01.

3.1. Walking task

A three-way repeated measures ANOVA (3 Preparation Velocities × 3 Eye Heights × 8 Time Intervals) performed on

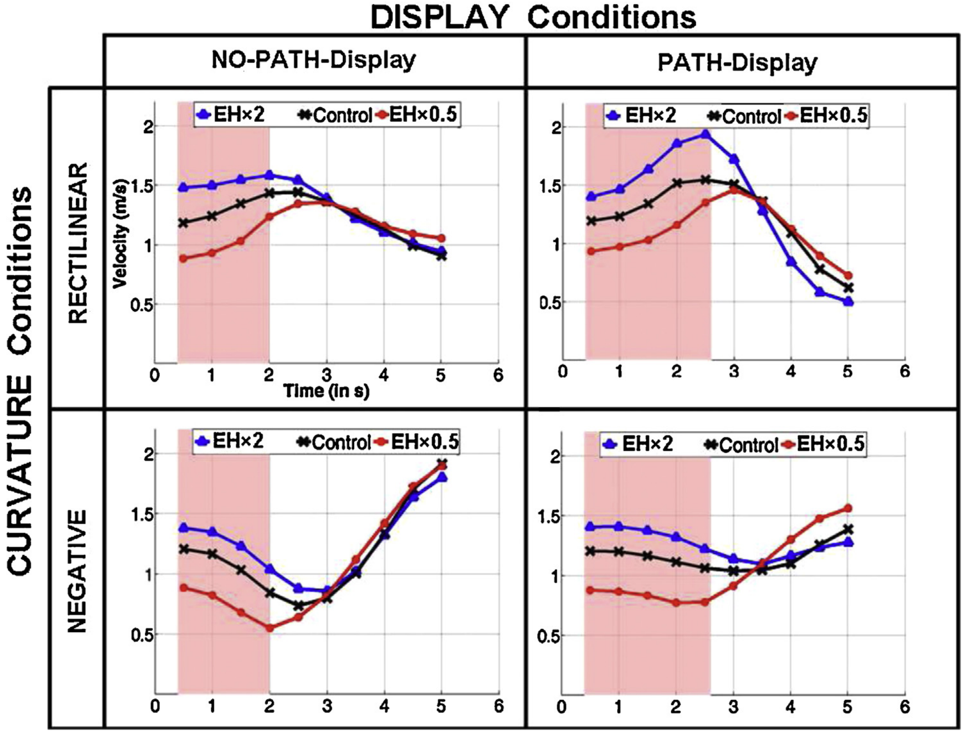

Fig. 3. Changes in average walking speed over time as a function of the Display Condition, Curvature and Eye Height (×, ▲ and ● symbols correspond to the EH, EH×2 and EH×0.5 conditions, respectively). The colored zone represents the time interval during which speed profiles were differentiated.

displacement speed revealed a significant main effect of Eye Height ($F(2,14) = 109.55$, $p < 0.01$, $\eta 2p = 0.94$) and Time Interval ($F(7,49) = 12.60$, $p < 0.01$, $\eta 2p = 0.64$), but no significant effect of Preparation ($F(2,14) = 0.30$, $p > 0.01$, $\eta 2p = 0.04$). A posteriori comparisons revealed that participants significantly increased their walking speed when Eye Height was increased (EH×2), compared to the control condition (EH) (1.30 vs. 1.19 m/s). Conversely, they significantly decreased their walking speed relative to the control condition when Eye Height was decreased (EH×0.5) (0.93 vs. 1.19 m/s). These results are consistent with those obtained by François et al. [6]. A decrease in Eye Height leads to an overestimation of walking speed and consequently a slower pace (and vice versa). Moreover, the fact that walking speed in the preparation phase did not affect speed adjustments in the test phase led us to remove this factor from the remaining analyses.

3.2. *Interceptive task*

Performance. Three-way repeated measures ANOVA (3 Eye Height × 2 Curvature × 2 Display Conditions) carried out on the Success Rate revealed a significant effect of Display ($F(1,7) = 15.06$, $p < 0.01$, $\eta 2p = 0.69$). A posteriori comparisons revealed that participants achieved a better SR in the Path-Display than in the No-Path-Display condition (81.7 vs. 75.5%, respectively). A three-way repeated measures ANOVAs (3 Eye Height × 2 Curvature × 2 Display Conditions) performed on the Constant Error revealed a significant effect of Curvature ($F(1,7) = 29.70$, $p < 0.01$, $\eta 2p = 0.81$). A posteriori comparisons revealed that participants arrived slightly early at the interception point (negative error: −0.1 m) in the Negative-Curvature condition and slightly late (positive error: 0.18 m) in the No-Curvature condition.

Speed profiles. A four-way repeated measures ANOVA (3 Eye Height × 2 Curvature × 2 Display Conditions × 10 Time Intervals) performed on walking speed revealed significant effects of Eye Height ($F(2,14) = 69.67$, $p < 0.01$, $\eta 2p = 0.91$) and Curvature ($F(1,7) = 46.65$, $p < 0.01$, $\eta 2p = 0.87$). We also found significant interactions between: Eye Height and Time Interval ($F(18,126) = 27.92$, $p < 0.01$, $\eta 2p = 0.79$); Curvature and Time Interval ($F(9,63) = 116.58$, $p < 0.01$, $\eta 2p = 0.94$); Display and Time Interval ($F(9,63) = 22.66$, $p < 0.01$, $\eta 2p = 0.76$); and Eye Height, Curvature, Display and Time factors ($F(18,126) = 2.14$, $p < 0.01$, $\eta 2p = 0.23$). Post hoc analyses of this last interaction revealed several important effects. First of all, variations in walking speed were influenced by curvature manipulations depending on whether (or not) the path was displayed. In the No-Path-Display condition (left panels in Fig. 3) the Negative-Curvature condition led to more pronounced changes in displacement speed than the No-Curvature (rectilinear) condition. More precisely, the Negative-Curvature condition led to a decrease in displacement speed in the first part of the trial followed by a pronounced increase in the second part. Conversely, in the Path-Display condition, the reverse effect was observed. Displacement speed changes were more pronounced in the No-Curvature (rectilinear) condition than in the Negative-Curvature condition. In this latter condition, displacement speed increased in the first part of the trial, followed by a pronounced decrease in the second part. Finally, marked difference in initial displacement speed in the three Eye Height conditions (whatever the experimental condition, i.e., Curvature and Display) indicated that we had succeeded in manipulating an optical correlate of displacement speed. Interestingly, a posteriori comparisons indicated a late convergence of speed profiles corresponding to the three Eye Heights in the Path-Display condition, while the same was not seen in the No-Path-Display condition (red zones in Fig. 3). While speed profiles can still be differentiated 3 s after the beginning of the trial in the Path-Display condition, the convergence appears earlier (after 2 s) in the No-Path-Display condition.

4. Discussion

Following the work of Morice et al. [1] and François et al. [6] this study examined the optical correlate of self-motion speed GOFR, when intercepting a moving target while walking. We hypothesized that when the target path is shown, the GOFR would be used to control the interceptive action (as it is a factor of the MRV strategy). By using this strategy participants should be unable to cancel the difference between the required velocity allowing them to intercept the target and their real speed due an over(under)-estimation of their real speed as GOFR was manipulated. Therefore, participants should fail in the task. Conversely, we hypothesized that the CBA strategy, which does not rely on self-motion speed perception, would be used when the target path is not shown. This strategy should not only enable the participant to succeed in the task, but also produce different speed profiles as the curvature of the target path is manipulated. Our results provided limited support for these predictions.

Consistent with our predictions, our results revealed that GOFR was used to control action when the participants walked at their preferred speed. Indeed, a decrease in walking speed was observed when the optical speed specified by the GOFR gave rise to an overestimation of actual speed (i.e., when Eye Height was decreased), and vice versa. These results are consistent with those of previous experiments [5,6]. Next, we focus on the influence of this misperception of self-motion speed in the control of interceptive tasks.

In the No-Path-Display condition, participants succeeded reasonably well (75% success rate) in completing the task. Moreover, they produced different speed profiles as the curvature of the target path was manipulated. More precisely, the Negative-Curvature condition led to an overall decrease in displacement speed in the first part of the trial, followed by an overall increase in the second. The No-Curvature condition gave rise to very little variation in displacement speed. This influence of curvature manipulation on speed profiles is consistent with studies in which path curvature was manipulated [1,2]. Finally, Eye Height manipulations did not change behavior. These results are consistent with the argument that a CBA strategy is used in the natural environment.

In the Path-Display condition, once again overall performance was good (81% success rate) and speed profiles were influenced by manipulations of target path curvature. However, although Eye Height manipulations did not lead to clearly distinguishable speed profiles in the overall trial, speed profiles converged later than in the No-Path-Display condition. These results merit discussion.

At first sight, speed profiles in the Path-Display condition seem to invalidate the use of the GOFR as part of an MRV strategy. Nevertheless, we argue that a more complex strategy is being used. Remember that, in theory, an MRV strategy should lead to systematic failures in the interception task (in both $\text{EH}\times0.5$ and $\text{EH}\times2$ conditions). This should be seen in a Constant Error of around ±0.8 m, due to a misperception of self-motion speed and, as consequently, distinct speed profiles in the overall trial. While the latter prediction was confirmed in the first 3 s of the trial, the former was not. These results suggest that participants relied on an MRV strategy at the beginning of the trial and modified their displacement speed accordingly – up until the moment when it became clear that they would not be able to intercept the target (around 2 s before head–ball contact). The perceived lack of correspondence between the regulation of their existing behavior and the adjustments required to succeed in the task may have driven them to use another strategy (possibly the CBA strategy).

Returning to the main question addressed by our study, self-motion speed perception is not a *sine qua non* condition for intercepting a moving target while walking. Intercepting a moving target can be achieved through prospective control, despite within trial changes of the target speed [7], between trial changes in the informational context [8] or changes in the optic flow from time to time [8,9]. Depending on environmental constraints agents can rely on different perceptual degree of freedom, allowing them to pick up the rate of change of the bearing angle with different sensory modalities [10], different optical cues [8], or by switching from a pure prospective control (i.e. CBA) to a prospective control using predictive information (i.e. MRV) [1]. Our study shows that the GOFR can be seen as a perceptual degree of freedom, among the others previously reported, that the agent can use to perform the task. In sum, this study underlines the flexibility of the perceptual-motor organization underlying the control of goal-directed behavior. It shows that not only different perceptual-motor strategies can operate depending on the informational content of the environment, but also that different strategies can operate jointly in task completion. Such flexibility should rely on the ventral and dorsal system contributions [11,12]. Indeed, whereas online adjustments of walking speed performed during the operation of an interception strategy (e.g., CBA or MRV) should be enhanced by the dorsal stream functioning, the switch from an interception strategy to another should be in charge of the ventral stream. An examination of the conditions of this complementarity offers a very challenging perspective for future work.

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