The visual control of ball interception during human locomotion
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Abstract

According to the required velocity model, on-line modulations of movement acceleration are performed on the basis of an optically specified difference between required and current behavior. Can this model account for observed displacement regulations in an interceptive task requiring locomotive displacements? In the present study, a virtual reality setup was coupled to a treadmill. Subjects walking on the treadmill were required to intercept a virtual ball approaching at eye-level by adjusting their velocity, if necessary. While the required velocity model could partially account for displacement regulation late in the interception, it was ineffective to explain early regulations. The possible use of a bearing angle strategy to control displacement regulation and the possible degree of complementarity of these strategies are discussed.

Keywords: Perception-action coupling; Locomotion; Law of control; Bearing angle strategy; Goal-directed action

Intercepting or avoiding a moving object is one of the most complex abilities characterizing the human perceptive-motor repertoire. It requires on-line movement regulations, based on instantaneously available information, to accommodate to a future event [9]. This is the case when driving a car, when moving through a crowd, or when intercepting a moving ball. While the information substrate possibly used in this kind of task has received special attention [10,14], very few integrative models exist which describe not only the information but also how the information is used in the control process.

The required velocity model [1,2,13] constitutes a rather isolated attempt to bridge the gap between perception and action. According to this model, on-line modulations of movement acceleration are performed on the basis of an optically specified difference between required and current behavior (Eq. 1). This continuous updating of the movement with respect to current information [15] guarantees success. In one study [13] a one-handed catching task was used in which the hand was constrained to move along a single lateral direction while the angle of approach of the ball was varied. In this model, the required behavior corresponds to a required hand velocity expressed by the ratio between the current lateral distance separating the hand from the ball and the time remaining before the ball reaches the movement axis (Eq. 2) (see [5] for an optical specification of this ratio). The current behavior corresponds to the actual velocity of the hand.

\[ X_{req} = \frac{X_b - X_h}{TC} \]  

where \( X_{req} \) is hand acceleration, \( X_{req} \) is the required velocity, \( X_{cur} \) is the current velocity, \( X_b \) is the current lateral ball position, \( X_h \) is the current hand position, \( TC \) is the time remaining before the ball reaches the movement axis and \( \alpha \) and \( \beta \) are constants.

According to this model, all the subject has to do is to adjust hand acceleration to cancel the difference between required and current behavior.

Recently this model received empirical validation [11,12]. In these two experiments the subjects were asked to intercept moving objects while various parameters were manipulated, e.g. angle of approach, ball speed, duration of presentation. The results show adaptations of hand kinematics that match the predictions made on the basis of the
the ball reaches the axis (TC). The bearing angle produced behavior along the Y direction (Fig. 1). The required velocity model can be simply reformulated by expressing both required and current behavior occurred on average 300 ms before contact and was maintained until contact. Moreover, if the subject’s hand was initially placed in the correct position to catch the ball (i.e. no movement necessary), movements away from this position occurred as soon as a lateral hand-ball distance was created, followed by reversal movements back to the correct position.

These results argue for the validity of the model under consideration, nevertheless they call for a few remarks. First of all, they were obtained using a task in which hand movements were mechanically constrained to one direction. While this added constraint can be justified insofar as it allows a more easy test of the model, it remains to be seen if the model applies to other, more realistic tasks. It is also worth mentioning that in the three previously cited studies [11,12,13], the movement times were between 1 s and 1.5 s. Consequently, one can ask if the same model can account for movement regulation when the interceptive task involves a larger time scale (around 8 s in the present experiment).

The present study was designed to explore the utility of the required velocity model for a longer time frame with a different task. Subjects were asked to move (locomotion displacement) in a specified direction (along the Y-axis) and to intercept with their head a virtual moving ball crossing their displacement axis. The required velocity model can be simply reformulated by expressing both required and produced behavior along the Y direction (Fig. 1).

Eight subjects with normal or corrected to normal vision participated in the present study. Informed consent was obtained prior to testing. The experimental set-up consisted of a virtual environment (Silicon Graphics) coupled to a treadmill (Gymroll). Subjects walked on the treadmill 0.6 m in front of the screen (3 × 2.3 m) on which the virtual scene was projected. The virtual scene consisted of an approaching ball (0.2 m diameter) and a textured floor. Displacements of the virtual environment were directly proportional to the displacements of the subject on the treadmill. Ball path kinematics were collected by the Silicon Graphics system (100 Hz) and subjects’ displacement kinematics were registered by an optical encoder positioned on the treadmill (100 Hz). The synchronization of the two systems allowed the computation of all displacements (ball and subject) in the same coordinate system. This set-up was chosen for obvious reasons: the task constraints are easy to manipulate while natural movement regulation behavior is maintained [4]. Subjects were required to intercept the ball approaching along a rectilinear path (26.56° with respect to subjects’ displacement axis) with a constant velocity (1.26 m s⁻¹) along a horizontal plane going through the head. The interception point was computed at the beginning of each trial on the basis of subjects’ initial velocity (mean velocity 0.81 m s⁻¹, SD 0.057 m s⁻¹), while the time taken by the ball to cross subjects’ displacement axis was kept invariant (7.5 s). Subjects performed the experimental task in three conditions: no change, acceleration and deceleration. In the no change condition, no velocity adjustments were required. In the other two conditions subjects had to either accelerate, or decelerate to intercept the ball. More precisely, in the acceleration and deceleration conditions, if the subject kept his velocity unchanged he would have been one meter short or ahead of the interception point, respectively. Subjects performed ten trials per condition, the order of conditions was randomized across all trials. Subjects received immediate performance feedback after each trial: a green (success) or red (failure) square projected in the center of the screen. A successful trial was one where the distance between the center of the ball and the center of the subject’s head was at most ±2 cm when the ball crossed the subject’s displacement axis.

Current error was computed every 10 ms during each trial and represents the error that would result if the current velocity had been kept invariant. Consequently, a current error that tends towards zero implies effective regulation of velocity. Performance measures were percentage of successful trials and the time-course of inter-trial variability of both velocity and current error (i.e. each half second during the last 6 s before contact). An increase in velocity variability indicates velocity regulations. In the assumption that these velocity regulations are effective, they should be accompanied by a decrease in current error variability. For the required velocity model analysis, the fit of the model to the recorded data was examined using multiple linear regression on each trial. The analyses were based on Eq. 1 and tested the extent to which acceleration depends upon the
velocity differential. The values of the two parameters of Eq. 1 (i.e., \( \alpha \) and \( \beta \)) were not set a priori but corresponded to the values that led to the better fit. The validity of the model was assessed by looking at the average percentage of the total variance explained by the model.

An initial ANOVA showed that the percentage of successful trials was not affected by experimental condition \( (F(2,14) = 1.125, P > 0.05) \). Subjects’ success rate was 61% in all three conditions (acceleration, deceleration and no change). This relatively poor success rate should not be too surprising as it is the result of the particularly stringent success criterion characterizing the task (spatial window: 4 cm, temporal window: around 30 ms). Subsequent ANOVAs were conducted on all trials (i.e. successful trials and failures, \( n = 240 \)). Velocity and current error variability profiles indicated an initial increase in the velocity variability 5 s before contact and a second increase 1.5 s before contact \( (F(11,77) = 34.085, P < 0.001) \) together with a decrease in the current error variability 5 s before contact onward \( (F(11,77) = 53.646, P < 0.001) \) (Fig. 2). These results reveal effective velocity regulations occurring very early in each trial.

The required velocity model analysis was conducted over the 240 trials. Multiple linear regressions were performed over six temporal ranges: 6 s before contact onward, 5 s before contact onward, ..., 1 s before contact. These analyses showed that the percentage of total variance \( (R^2 < 100) \) explained by the model during the last 6 s of the task was an inverse function of the remaining time (8.5%, 9.5%, 11%, 14.5%, 25% and 46% for the time periods 6, 5, 4, ..., 1 s before contact, respectively). An analysis of variance performed on the data after Z-transformation revealed an increase of the Z values 3 s before contact onward \( (F(5,35) = 261.294, P < 0.001) \). Hence, the required velocity model only predicts the observed kinematics in the vicinity of contact, accounting for (at best) 46% of the variance and cannot account for early velocity regulations (i.e., at 5 s before contact). This rather weak percentage of variance explained by the model could also highlight the need in future modeling work to integrate in some way a noise term in order to account for the inter trial variability inherent to the production of such behavior.

An additional analysis was performed in order to see whether an alternative strategy of maintaining a constant bearing angle [3] could explain the observed early velocity regulations. Bearing angle is the angle subtended at the point of observation by the current position of the ball and the direction of displacement (Fig. 1). Linear regression analyses were performed for each trial \( (n = 30) \) performed by a representative subject on the time-course of the bearing angle from the beginning of the trial until 2 s before contact. If the bearing angle strategy had been used, the regression analyses should have zero gradient. The analyses revealed, for each trial, variations of the bearing angle across time \( (P < 0.05 \text{ and mean } R^2 \text{ values 0.73}) \). Nevertheless, the slopes were not statistically different from zero.

Fig. 2. Time course of both mean displacement velocity and current error profiles with the associated variability (error bars) in the acceleration condition (diamond), the no change condition (square) and the deceleration condition (triangle). The analyses reveal an initial increase in velocity variability 5 s before contact and a second increase 1.5 s before contact together with a decrease in the current error variability from 5 s before contact.

Fig. 3. Mean bearing angle profiles for every successive 0.5 s interval from 6 s until 1 s before contact, and their associated variability. The analyses reveal that the bearing angle is kept constant in the first part of the trial. Bearing angle only changes in the last 2 s before contact.
velocity of the ball at the beginning of the trial (0.05 m s\(^{-1}\)) is below the perceptual threshold (0.08 m s\(^{-1}\)) [6]. This could explain why subjects would use a bearing angle strategy initially and then could opt for a required velocity strategy when the expansion pattern is easily perceptible, i.e., at the end of the trial. A simple way to test the two hypotheses would consist in manipulating the expansion information during the last seconds before contact. The use of a bearing angle strategy should not suffer from this manipulation.

The present study illustrates the adaptive capacity of the perceptual-motor mechanisms underlying goal-directed locomotion. Rather than emphasizing the (real) limits of the required velocity model we prefer to keep in mind the diversity of the mechanisms available. Discovering the range of action of these mechanisms and eventually how these mechanisms cooperate offers a very interesting challenge for future work.

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