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Visual Guidance of Goal-Oriented Locomotor Displacements: The Example of Ball Interception Tasks

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This review focuses on a particular aspect of the visual guidance of goal-oriented locomotion, the interception of a moving object. The first part of this review presents the two perceptual strategies proposed so far: optical acceleration cancellation (OAC) and linear optical trajectory (LOT). The current state of the debate between the advocates of these two strategies is then discussed. A few final remarks attempt to reframe the debate relative to theoretical approaches of perception and action.

This review focuses on a particular aspect of the visual guidance of goal-oriented locomotion, the interception of a moving object. This question was recently brought up in a debate ("The Outfielder Problem") on the perceptual strategies used in baseball by outfielders trying to catch a fly ball hit by the opposing team's batter (see Dannemiller, Babler, & Babler, 1996; Jacobs, Lawrence, Hong, Giordano, & Giordano, 1996; McBeath, Shaffer, & Kaiser, 1996).

To begin, the information likely to be used in this type of task must be described. Cutting and Vishton (1995) proposed dividing the space surrounding the subject into three zones: personal space (up to 5 meters), action space (up to 50 meters), and vista space (on to infinity). The visual guidance of goal-oriented displacements takes place mainly in action space. Given that the efficiency of binocular informa-

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tion decreases linearly with distance, such information is not very useful for visually guiding goal-oriented displacements in action space. Moreover, because the ball's optical expansion pattern cannot be perceived in the action space either, information that includes this component must be ruled out. Given the previously mentioned limitations of the human perceptual system, the formal models that have been proposed involve monocular information based on the optical patterns displacement generated by the moving ball. Following Chapman's (1968) original model, only Todd (1981) and Brancazio (1985) took an interest in the information likely to be used in this type of task. More recently, Michaels and Oudejans's (1992) work triggered a new wave of research that sparked off a large debate(e.g., Dannemiller et al., 1996; McBeath, Schaffer, & Kaiser, 1995a).

The first part of this review presents the two perceptual strategies proposed so far: optical acceleration cancellation (OAC) and linear optical trajectory (LOT). The current state of the debate between the advocates of these two strategies is then discussed. A few final remarks will attempt to reframe the debate relative to theoretical approaches of perception and action.

OPTICAL ACCELERATION CANCELLATION

Chapman (1968) was the first to propose that one of the potential sources of information in mobile interception tasks giving rise to a locomotor displacement was the vertical optical acceleration of the ball. This information is thought to allow the subject carrying out such a task to position himself in the right place at the right time. The player using this strategy has only to cancel the optical acceleration of the ball by producing the appropriate locomotor displacement. Brancazio (1985) criticized the OAC theory because it ignores the resistance of the air and, using simulations, showed that if air resistance is taken into account, substantially different ball trajectories are obtained. However, it seems that this argument need not be regarded as invalidating Chapman's (1968) perceptual strategy. Indeed, the OAC strategy requires the subject to adapt his locomotor displacement pattern online, based on information that specifies the "state of the actor-environment system" (Bootsma, Fayt, Zaal, & Laurent, 1997). In the research conducted to date, optical acceleration is denoted $d^2(y)/dt^2$ (Michaels & Oudejans, 1992) or $d^2(\tan\alpha)/dt^2$ (e.g., McLeod & Dienes, 1993), depending on whether the model is based on plane or angular geometry (Figure 1; Equation 1).

$$\tan\alpha = H/D = y/r = y \tag{1}$$

If the optical acceleration is positive, the player knows the ball will land behind him; if it is negative, he knows it will land in front of him. An optical acceleration

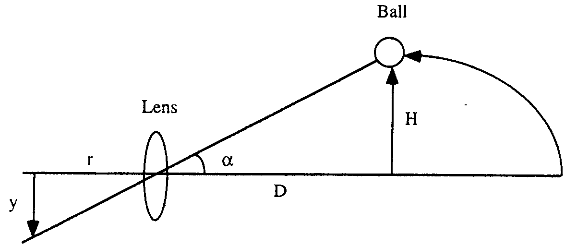

FIGURE 1 Relation between angle α, subtended at the observation point by the ground and the ball, and the ball's optical height on a projection plane located at a distance of $r = 1$ from the crystalline lens of the eye. D is the instantaneous horizontal distance separating the lens from the ball, and H is the instantaneous height of the ball.

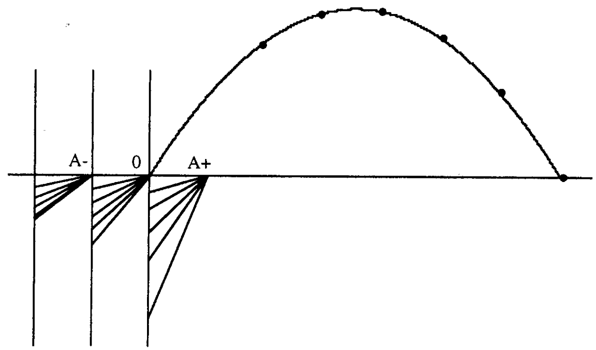

FIGURE 2 Optical displacement patterns observed by a player located behind the ball's landing point (A–: negative optical acceleration), at the landing point (0: null optical acceleration), and in front of the landing point (A+: positive optical acceleration). Air resistance is not considered here.

of zero (Equation 2) informs him that he will be located in the right place at the right time (Figure 2).

$$d^2(\tan\alpha)/dt^2 = 0 \tag{2}$$

Contrary to what Figure 2 might suggest, the OAC strategy does more than just allow the player to choose a given mode of action (Warren, 1988), that is, move forward, backward, or not at all. Once the action has begun, the strategy also allows him to control his action online to get to the right place at the right time. By zeroing out the vertical optical acceleration, the player is informed about whether the displacements produced are valid for the task being executed (Figure 3). Note that the player does not know in advance when and where the ball will land.

Contrary to what McBeath et al. (1995a) claim, OAC does not require moving at a constant speed (Figure 3). OAC works whenever the ratio d(tanα)/dt is constant, regardless of the value of the constant (McLeod & Dienes, 1996). There does indeed exist a particular value of this ratio for which the corresponding displacement at a constant velocity should take the player to the right place at the right time (Chapman, 1968). However, even in this case, as the actor starts from stationary, the initial part of the displacement is necessarily accelerated (Babler & Dannemiller, 1993; McLeod & Dienes, 1996). For all other values of the ratio, the displacement speed changes necessarily as the player approaches the ball.

LINEAR OPTICAL TRAJECTORY

According to McBeath et al. (1995a), all a player has to do to get to the right place at the right time is "linearize" the optical displacement of the ball by producing the appropriate locomotor displacement, that is, by keeping the optical trajectory projection angle (ψ) constant. To do so, the changes over time of the vertical angle (α)

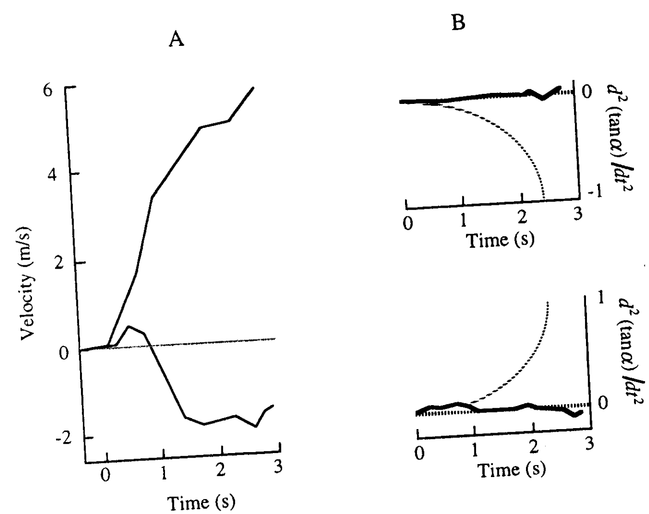

FIGURE 3 (A) Velocity curves characteristic of the running path of a player controlling his displacement online, for a ball projected in front of him (positive velocity) and behind him (negative velocity) in a ball interception task. (B) Time course of the vertical optical acceleration as it would appear if the player remained stationary throughout the trial (dotted lines) and as it appears if the player moves (solid lines; based on McLeod & Dienes, 1993).

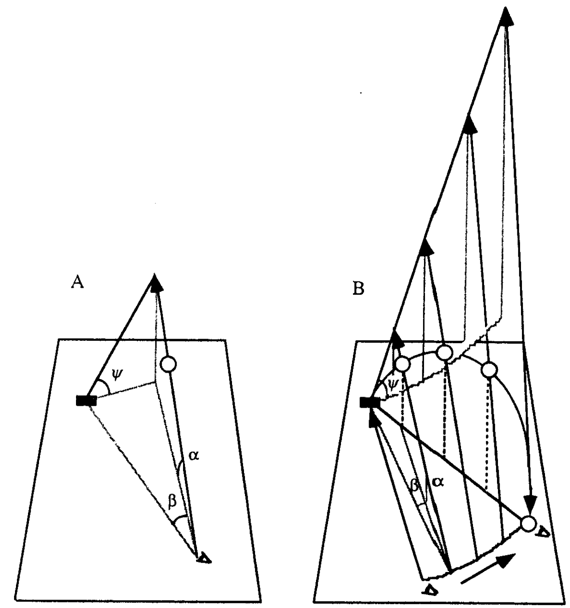

FIGURE 4 (A) Optical quantities "involved" in the LOT strategy: optical trajectory projection angle (ψ), vertical angle (α) subtended at the observation point by the ball's instantaneous location and the horizontal, and horizontal angle (β) subtended at the observation point by the ball's instantaneous location and the ball's launching point. (B) The LOT strategy is based on the linearization of the ball's optical displacement (i.e., keeping angle ψ constant): this means that angles α and β must vary proportionately (based on McBeath et al., 1995a).

and the lateral angle (β) subtended at the observation point by the ball's launching point (or any other fixed point in the environment), and its current location must stay proportional (Equation 3; based on McBeath et al., 1995a; Figure 4).

$$\tan\psi = \tan\alpha / \tan\beta = C_\psi \qquad (3)$$

This perceptual strategy requires keeping the optical trajectory projection angle constant via the cancellation of the curvature of the ball's optical path, which is achieved by moving in the appropriate way. Consequently, using the LOT strategy has repercussions on both the shape and the kinematic properties of the locomotor displacements produced. "Extreme" values for angle ψ, that is, ones that approach 0° or 90°, force the player to produce high-velocity locomotor displacements with trajectories that have very high curvature, to keep α and β proportional. According to McBeath et al. (1995a), then players are more in a position to choose optical trajectory projection angles close to 45°, which lead to "economical" displacements where the curvature is slight and the displacement velocity is low (inverted U-shaped curve).

THE DEBATE

Points of Agreement

Two online adaptation strategies. Both of these perceptual strategies (LOT and OAC) are quite elegant in the sense that they are not based on any knowledge of the properties of the to-be-intercepted ball and its trajectory; they tell the player about the state of the actor–environment system (Bootsma et al., 1997). This gives them some original predictive capabilities. They do not supply quantitative information (expressed in metrical or intrinsic units of measure) but simply tell the player whether the move being made is the right one for the task at hand. If the player does in fact use one of these perceptual strategies, he does not know in advance where or when the ball will land; he is simply using an "online adaptation strategy" (Peper, Bootsma, Mestre, & Bakker, 1994) that will lead him to the right place at the right time.

The arguments stated against these strategies have mostly been obtained from field observations (Adair, 1995; Chodosh, Lifson, & Tabin, 1995; Jacobs, 1995). Chodosh et al., for example, viewed videotapes of 179 ball catches in professional baseball games. Contrary to what is assumed in online adaptation strategies, the players were usually found to be stationary at the time they came in contact with the ball. This suggests that highly skilled players use a strategy that allows them to predetermine the place and time of landing (Saxberg, 1987a, 1987b) rather than an online adaptation strategy. However, some aspects of the work of Chodosh et al. remain unclear, therefore limiting the interest of the results presented. Some information, such as the sample frequency, the nature of the ball trajectories, or the criterion used to determine that the actor is stationary at contact, is not reported. Moreover, the LOT strategy is flexible, insofar as the optical trajectory linearization it involves is independent of the optical trajectory projection angle "chosen" (McBeath et al., 1995b). Maintaining the linearity of the optical trajectory will give rise to locomotor displacement patterns that differ and consequently will result in different velocities at contact, as a function of the value of the optical trajectory projection angle chosen. McLeod and Dienes (1996) report results that are compatible with the use of an online adaptation strategy. They analyzed the locomotor displacement patterns produced by a player when, for a given landing point, the ball's launch angle and velocity varied (i.e., the player had a variable amount of time to get to the landing point). The results showed that in every case the player was not standing still at the ball's landing point but had

chosen a displacement pattern that enabled him to arrive at the contact point at the same time as the ball.

The second major criticism of online adaptation strategies concerns the fact that they require permanent visual anchoring on the ball. However, field observations have proven that this is not always the case (Chodosh et al., 1995; Jacobs, 1995). McBeath et al. (1995b) stressed that until an analysis is conducted to determine the minimal sampling frequency required for maintaining a linear displacement, any statements on this subject should be treated with caution.

Points of Disagreement

The issues that oppose the advocates of the two perceptual strategies hinge on (a) potential implementation problems, (b) the respective scopes of the two strategies, and (c) the interpretation of the results.

Implementation of the strategies. Different parameters are controlled in the two strategies described. OAC is based on the control of a temporal parameter. LOT is based on the cancellation of the curvature of the optical displacement and thus on the control of a spatiotemporal parameter (Dannemiller et al., 1996). The question of how these two strategies are implemented adds fuel to the debate. McBeath et al. (1995a), for instance, speak of the possible limitations of the human visual system for perceiving optical acceleration. Various studies have, in fact, questioned human sensitivity to optical acceleration (e.g., Todd, 1981). According to Babler and Dannemiller (1993), Todd's (1981) results are due to the use of optical acceleration rates that are below the detection threshold. They showed that as soon as the acceleration gets high enough—that is, when the optical velocity ratio is above the threshold (estimated at 20% by the authors), as it is in virtually all trajectories not destined to strike the actor between the eyes—discrimination of the ball's landing place based on this information gets much better. Not only the vertical acceleration exceeds the threshold as soon as the actor is not on a collision course with the ball, but also the threshold is passed earlier when the remaining distance to cover is large. Moreover, Tresilian (1995) showed that it was indeed possible to implement the OAC strategy even when the constraints that limit human performance are considered (including difficulty discriminating optical acceleration). Note, finally, that various perceptual systems (visual, vestibular, proprioceptive, etc.) may contribute jointly to detecting vertical optical acceleration (Stoffregen & Riccio, 1988; Oudejans, 1996).

Concerning the LOT strategy, it seems that the human visual system is in fact able to detect optical curvature (Werkhoven, Snippe, & Toet, 1992). In their study, Werkhoven et al. (1992) show that the visual system is more sensitive to changes of direction than to the changes of optical velocity. Although no study has shown that the degree of sensitivity to the optical curvature is sufficient to make the LOT strategy operational (Dannemiller et al., 1996), the results of Werkhoven et al. (1992) lead us to think that the actor is able to implement the LOT strategy in ball catching with locomotor displacements.

Scope of the strategies. McBeath et al.'s (1995a) main criticism of OAC pertains to the fact that it is limited to direct approaches to the ball. They contend that a direct approach is only a special case because most ball catches require implementation of a perceptual strategy that controls both forward–backward and sideways movements.[1] This is why McBeath et al. propose the LOT strategy, which uses the optical trajectory of the ball in the horizontal and vertical axes. It is noteworthy that Chapman (1968) was already aware of this limit, leading him to propose a strategy with two distinct parts. The player was thought to continue controlling his anterior–posterior motion on the basis of OAC (i.e., by canceling $d^2 [\tan \alpha]/dt^2$) while controlling his lateral motion by canceling the horizontal optical displacements. The theoretical consequences of the strategy proposed by Chapman are discussed in the last paragraph.

Experimental results. The results gathered in the experimental work done so far are somewhat contradictory. One could wonder to what extent the heterogeneity of the experimental protocols used has not contributed to this situation (e.g., the characteristics of the ball trajectories, the modes of displacement, and the recording systems used vary widely between studies; Table 1). Note also the small number of sampled trials recorded, which raises the issue of the generalization of the results (Table 1). In spite of the methodological weaknesses, the studies provide some information on the nature of the strategy potentially used.

Michaels and Oudejans (1992) were the first to analyze the optical patterns of the ball's trajectory in catching tasks where the ball is approaching the player from directly in front. By comparing (a) the optical displacement curve resulting from the combined motion of the player and the ball and (b) the optical displacement curve that would have been observed if the player had remained stationary, they found that displacements were consistent with the cancellation of optical acceleration. McLeod and Dienes (1993, 1996) and Dienes and McLeod (1993) obtained similar results in the same type of task. McBeath et al. (1995a), on the other hand, tested the LOT strategy in catching tasks where the ball was approaching the player along an indirect trajectory. The results presented by McBeath et al. are compatible with the use of the LOT strategy in that (a) the moves linearize the optical trajectory of the ball and (b) in line with predictions based on the LOT strategy, they are curvilinear and have an

[1]The same type of criticism has been made of the optical variable *tau* (i.e., the inverse of the ball's relative expansion speed; Lee, 1976). This information source provides temporal information, the first order time to contact (Lee & Young, 1985) in the particular case of a direct approach. Whenever the approach is indirect, the optical displacement must be taken into account in order to obtain the first order time to contact (Bootsma & Oudejans, 1993).

TABLE 1
Summary Table of the Various Experimental Studies Aimed at Determining the Visual Guidance Strategies Implemented in Ball Catching Tasks Requiring a Locomotor Displacement

Trajectory	*Recording*	*Subjects–Trials Analyzed*	*Results*
Michaels & Oudejans (1992)			
Direct approach. Range: 6–25 m. Flight angle/flight time: variable. Subject's displacements: 2–10 m.	25 Hz digitization of head and ball	Experiment 1: 2 expert softball players/10 trials. Experiment 2: 2 expert softball players/7 trials.	Favor OAC
McLeod & Dienes (1993)			
Direct approach. Range: 50 m. Flight angle/flight time/ projection speed: 45°/3 s/20–25 m/s. Subjects' displacements: 2–10 m.	Digitization of head and reconstruction of ball trajectory	One expert baseball player.	Favor OAC
McBeath et al. (1995)			
Indirect approach. Range: 50 m. Flight angle/flight time/ projection speed: variable. Subjects' displacements: 2–15 m.	Experiment 1: 30 Hz digitization of head. Experiment 2: Ball trajectory recorded by camera fastened to subject's shoulder	Experiment 1: 2 amateur baseball players/28 trials. Experiment 2: 2 amateur baseball players/27 trials.	Favor LOT
Jacobs et al. (1996)			
Indirect approach. Range: approx. 50 m. Flight angle/flight time/ projection speed: 58°/4 s/5 m/s. Subjects' displacements: large (approx. 30 m).	5 Hz digitization of head and reconstruction of ball trajectory	?	Favor LOT in initial part of trajectory
McLeod & Dienes (1996)			
Direct approach. Range: varies from 40-50 m. Flight angle/flight time/projection speed: 45° or 64°/3 s/20–25 m/s. Subjects' displacements: 1–10 m.	8 Hz digitization of head and reconstruction of ball trajectory.	Experiment 1: 6 subjects (1 expert soccer player, 1 expert cricket player, and 4 novice cricket players)/6 trials. Experiment 2: 1 subject/6 trials.	Favor OAC

inverted U-shaped velocity curve. Jacobs et al. (1996) recorded a new series of ball catches involving backward–forward and sideways movements. Their results support the use of a strategy based on LOT during the initial portion of the ball's trajectory (i.e., within 2 sec after the ball is launched), where tan α and tan β increase linearly. However, in the final portion of the trajectory (i.e., within 2 sec before contact) when the player keeps tan α increasing linearly (contrary to what Jacobs et al. claim), tan β is approaching 0. These results suggest that the LOT strategy is no longer operational 2 sec before contact. Unfortunately, Jacobs et al. were not able to propose an alternative to LOT based on their experimental data.

Are the Two Strategies Complementary?

Dannemiller et al. (1996) simulated ball catches in which the players did not arrive in the right place at the right time, even though they kept the ball's optical trajectory linear. The simulations they produced, for example, had optical ball trajectory images that, although linear, contained reversal points reflecting a proportional decrease in tan α and tan β. This finding shows that the mere monitoring of the linearity of the ball's optical trajectory does not supply enough information to get the catcher to the landing point at the right time, hence McBeath et al.'s (1995a) requirement that tan α and tan β be proportional to each other and monotonically increasing. Dannemiller et al. wonder whether players can foresee the occurrence of such reversal points to control their displacements soon enough. They also say that even when the two conditions are satisfied (i.e., linearization of the optical trajectory and monotonic increase in tan α and tan β), the player may still not get to the landing point on time. These findings led Dannemiller et al. to contend that McBeath et al.'s strategy necessarily includes an additional constraint: OAC. Only this additional constraint can guarantee that no reversal points will be produced. In fact, McBeath et al. (1996) propose that the two strategies are complementary.

FINAL REMARKS

This review of the literature on the visual guidance of goal-oriented displacements calls for a few remarks. The only tangible accomplishment at the current time is the existence of two formal models of possible perceptual strategies (Chapman, 1968; McBeath et al., 1995a). It seems, moreover, that although the advocates of the two models are divided on this issue, human beings do, in fact, have the neural wiring capable of implementing both of the strategies described (Babler & Dannemiller, 1993; Tresilian, 1995; Werkhoven et al., 1992). Indeed, even though McBeath et al. think that, in the OAC framework, the extraction of the tangent of the vertical optical angle might cause a problem, we avoid drawing any analogies here between the formal characteristics of the information and the characteristics of the mechanisms in charge of its implementation (Runeson, 1977). In other words, "smart perceptual mechanisms" may be able to extract information no matter how complex it might be. Besides, no decisive experimental proof of the actual use of either of the strategies has been proposed yet. Only the experimental manipulation of one of the perceptual components of the two strategies, accompanied by quantitative predictions of the behavior produced, could really test the two strategies.

Before running any experiment, it seems important to improve the existing formalization. The "elegance" of the strategy based on OAC lies in its ability to capture the transformation patterns of the optical array, which offer direct and unequivocal access to the state of the actor–environment system (Bootsma et al., 1997; Michaels & Carello, 1981; Michaels & Oudejans, 1992). Michaels and

Oudejans stressed that the vertical optical acceleration has all the features of an invariant in the Gibson sense of the term. However, when the trajectory of the ball induces a horizontal optic component, the invariant is not sufficient to specify the state of the system, and the actor has to use another invariant (based in this case on the pattern of horizontal displacement; Chapman, 1968). Associating several invariants to access the relevant property of the actor–environment system deprives the perceptual process of its the parsimonious character. The necessity to use two invariants may also simply reflect the (temporary) inability of the researchers to formalize within one mathematical formula the generic invariant, which could be used whatever the trajectory. The same does hold true of the strategy proposed by McBeath et al. (1995a), to the extent that merely maintaining a LOT may turn out to be insufficient for gaining access to the current state of the actor-environment system, in which case recourse to some other invariant (such as vertical optical acceleration) is needed. McBeath et al. (1996) seem to adapt to this state by resolutely espousing the framework of cue theory (Gregory, 1966). Anyway, no integrated perceptual strategy, able to lead independently from the constraints the actor to the right place at the right time, can be found in the literature.

Moreover, the strategies proposed so far (LOT and OAC) do not account for the way in which information is integrated to control displacement (see Michaels & Beek, 1995, for a discussion). In this respect, the work of Bootsma and collaborators (Peper et al., 1994; Bootsma, 1988; Bootsma et al., 1997) is one of the first attempts to propose a unitary model of the relations between perception and action. For the task of catching a ball constrained on a single axis, Bootsma et al. (1997) proposed a strategy aiming at (a) optically accessing the relevant property of the actor–environment system (i.e., the required speed of the hand) and (b) integrating the information for a control of the movement (i.e., the acceleration would depend upon the gap between the required speed and the current speed). The strategy formalized by Bootsma et al. resembles the strategies of continuous control presented in this review. The actor is sure to be at the right place at the right time by regulating the movement on the basis of an invariant that gives access to the relevant property of the actor–environment system. Moreover, to its credit, the model presented by Bootsma et al. offers an integrating mechanism of the information to control the movement. The issue of the generalization of this type of model to all the interceptive tasks has to be addressed. For the tasks reviewed here, the displacement being not constrained on a single axis, the relevant property of the actor–environment system cannot be reduced to the sole required speed; the direction of the displacement of the actor has to be specified too.

It is our view that the future formalization will have to (a) identify the generic invariant used, (b) link this invariant with the relevant property of the actor–environment system, and (c) describe the modality of this integration of the information to control the displacement. In the current state of the art, the question of the visual guidance of locomotor displacements remains unanswered.

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