VISUAL EXTRAPOLATION OF BIOLOGICAL MOTION

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ABSTRACT

Curvature and velocity of human movements covary in a way described by an empirical relation known as the Two-Thirds Power Law. The visual system is particularly sensitive to this covariation, suggesting that this motor rule implicitly constrains perception. By using a visual extrapolation task, we investigated whether motion imagery is constrained as well. Preliminary evidence is presented favouring the notion that, depending upon eye movements being allowed or not, visual imagery is sensitive to the law of motion of the inducing stimulus.

In their general form, motor theories of perception claim that our perceptual systems take into account some features of the motor systems. In particular, it has been suggested that the process of perceptual selection is constrained by the implicit knowledge that the central nervous system has with regard to the movements it is capable of producing (Scheerer, 1984, 1987; Viviani, 1990; Viviani and Stucchi, 1992). Since the early work of Johansson (Johansson, 1973), it is known that humans are able to recognize in a striking consistent manner the movement of a human body, even if it is shown in a rather reduced way, that is, through its dynamic template obtained only with single visible markers placed on some crucial points (i.e., joints) of the body. Subsequent work by many research groups has detailed such capabilities, showing in particular that our perceptual system is very well attuned to a peculiarity of human movement, namely, a particular relation between velocity and curvature (Viviani and Stucchi, 1989, 1992; de' Sperati and Stucchi, 1995; Viviani et al., 1997).

Let's briefly introduce this relation. The movement of a point in an (x, y) plane can be thought of as the conjunction of two components: the trajectory $y = f(x)$, that describes its shape and the law of motion $s = s(t)$, that describes the increase in time of the length of the trajectory from the starting position. Mathematically, the two components are independent: knowing the shape, one cannot infer the law of motion and viceversa. However this independence often vanishes when the movement represents a physical event. For instance, when an unconstrained inertial mass moves according to Newton's dynamic equation, both the trajectory and the law of motion are uniquely defined by the force field. Consequently, they are functionally related: any systematic relation between kinematics and trajectory indicates the existence of a force field that dynamically constraints the two components.

Human movements is an example of one such constraint. As first described in free-hand movements (Viviani and Terzuolo, 1982), the human motor system cannot produce spontaneous movements in which curvature and velocity are independent (Viviani and

Schneider, 1991; Lacquaniti, Terzuolo and Viviani, 1983; de'Sperati and Viviani, 1997). Instead, these two parameters covary, and in simple movements like drawing ellipses, their relationship is well described by the relation

$$V(t) = K(t)\left(\frac{R(t)}{1+\alpha R(t)}\right)^{1-\beta} \qquad \alpha \le 0, K(t) \le 0 \qquad \textbf{(1)}.$$

between the tangential velocity V(t) and the radius of curvature R(t) of the trajectory . Because in adults the experimental value of the parameter β is very close to 1/3, the term *two-thirds power law* has been suggested to refer to the regularity expressed by Equation 1. The parameter α is 0 when the trajectory of the movement has no points of inflection. The parameter K is constant over relatively long segments of the trajectory and depends on the general tempo of the movement and on the length of the segment (Viviani and McCollum, 1983). Changes in K tend to occur either at points of inflections or at junction between figural units (Lacquaniti, Terzuolo and Viviani, 1984; Viviani, 1986; Viviani and Cenzato, 1985).

It can be demonstrated that if the movement is constrained by Equation 1, the law of motion *s*= *s(t)* is completely determined by the shape of the trajectory. A 2D movement that follows a certain trajectory qualifies as a biological movement if and only if the velocity varies along the trajectory in the specific way prescribed by Equation 1 with β=1/3. Thus, in this paper we refer to this kind of movement as biological movement.

The visual system is particularly sensitive to biological movements. A perceptual bias has been shown in the form of two visual illusions produced by moving stimuli that do not satisfy the two-thirds power law (Viviani and Stucchi, 1989, 1992): (i) when a dot moves along a circular trajectory with an instantaneous velocity that would characterize a dot moving along an elliptical path with a kinematics specified by the two-thirds power law (i.e., a circular motion with accelerations and decelerations), subjects perceived an elliptical path, as if the geometry of the figure defined by the moving dot were influenced by some implicit knowledge about the kinematics rules; (ii) the velocity of a dot moving on elliptical trajectories is perceived as constant only when velocity and curvature covary accordingly with the two-third power law rule (consider that this condition correspond to an objective highly non-uniform velocity).

Further evidence has been obtained in modalities other than vision: a passive hand movement induced artificially by a computer controlled robot is perceived correctly only if the movement is in compliance with the constraints present in active gesture (Baud-Bovy and Viviani, 1998). Otherwise, not only there arise large kinaesthetic illusions, but is actually impossible to reproduce accurately with the hand a motion - even when perfectly predictable - that violates the power law. This finding is in keeping with the impossibility to track accurately a visual target with the hand (Viviani and Monoud, 1990) or with the eyes (de'Sperati and Viviani, 1997) if its motion does not comply with the two-thirds power law.

Previous work showed that, when the dynamic visual stimulus is in fact a faithful representation of a biological movement, the perceptual system can take advantage of the peculiar quality of the movement in order to predict its future course. By presenting on a computer screen a portion of the dynamic trace recorded in the course of cursive handwriting, subjects could predict with good accuracy which of the two possible continuation of the gesture had been followed in the course of writing (Kandel, Viviani and Orliaguet, 2000). If the natural kinematics (but not the geometry) of the traces were experimentally manipulated by changing the exponent β in the law of motion, the accuracy dropped drastically.

All these findings corroborate the hypothesis that biological motion is treated in a rather privileged way. It is therefore plausible that those visual functions more or less directly concerned with motion processing may take advantage of this privilege: they might work faster, or better, when an observed motion is in fact a biological motion. The present work addresses this issue by investigating whether motion imagery capabilities depend on the to-be imagined stimulus complying or not with the two-thirds power law. To induce mental imagery, a visual extrapolation task was devised.

Methods

Subjects. Nine adult observers (four females and five males) took part in the experiment. They had normal or corrected-to-normal vision.

Apparatus and Stimuli. The experiment was run on a computer equipped with a 21 inch colour monitor (resolution of 640x480 pixels and a refresh rate of 75 Hz). A white spot ($\varphi = 0.002$ deg) moved clockwise on a dark background along an elliptical path slanted by 45 deg. The major semiaxis of the ellipse (Bx), had a length of 8.0 cm while the minor semiaxis (By) was 3.5 cm long. The perimeter was 33 cm. The tangential velocity of the spot had a maximum of 15.65 cm/s and a minimum of 6.8 cm/s. According to the kinematical condition (see below), the peak tangential velocity occurred at either the point of maximum radius of curvatures of the ellipse or at its minimum. (i) In the first condition (Biological motion) the tangential velocity of the stimulus was related with the radius of curvature of the trajectory through equation (1). In this case the instantaneous tangential velocity increased with the radius of curvature. (ii) In the second condition (Non-biological motion), the instantaneous velocity of the spot was the velocity that would have a spot moving according to the two-thirds power law along an ellipse rotated by 90 deg. In this case, the instantaneous tangential velocity decreased with the radius of curvature. In both conditions the period was 2.637 s to complete one cycle (average velocity 12.5 cm/s).

Task and Experimental procedure. The elliptical trajectory was displayed on the monitor throughout the experiment. The moving spot (inducing stimulus) completed either 2.0, 2.25, 2.5 or 2.75 cycles before disappearing. This corresponded to four vanishing positions (at 90, 180, 270 or 360 deg). The vanishing of the dot was accompanied by a 2500 Hz beep, lasting 55 ms. Then a second beep was emitted either 220, 440, 659, 879, 1099, 1319, 1538, 1758, 1978, 2198, 2418 and 2637 ms after the first beep.
Subjects seated 60 cm in front of the monitor in a dimly lit room. They were instructed to pay attention to the moving spot so to mentally protract its motion throughout the inter-beep interval. The second beep signalled the end of the trial, and subjects had to move the mouse cursor on the point where they reputed the imaginary spot to be at the time of the second beep, and press a button. The x-y coordinates of the mouse were recorded. The experiment was divided in two sessions: for one group of four subjects central fixation was required, while the second group of five subjects was free to pursue the moving spot. In order to prevent fading effects, across the trials the fixation cross was actually displayed in randomly selected positions within $\pm$ 0.5 deg from the geometrical centre of the ellipse. Before starting the experimental session, subjects familiarized with the task.
Thus, the experimental design had three completely crossed within-subjects factors: [Stimulus kinematics (SK, 2 levels: Biological vs. Non-biological); Vanishing position (VP, 4 levels: 90, 180, 270 and 360 deg); Interrogation time (IT, 12 levels: from 220 to 2637 ms, in steps of 200 ms)] and one between-subjects factor [Ocular Motility (OM, 2 levels: Fixation vs. Free-

viewing)], for a total of 2x4x12=96 trials per session administered in a completely random order. For the statistical analyses, an ANOVA for repeated-measures with one additional between-subjects factor was used. The dependent variable was the phase of the response computed from the x-y coordinates of the mouse.

Results

In Figure 1 are reported both the phase of actual, but in fact absent, stimulus (virtual target, open circles) and the phase of the response as a function of the Interrogation time, for the Biological and Non-biological conditions.

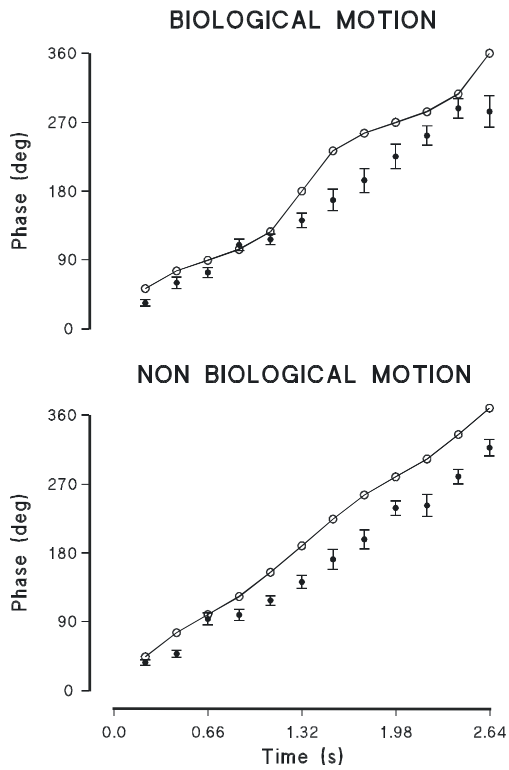

Figure 1. Phase of the response as a function of the Interrogation time (filled circles) together with the expected phase (open circles), for the Biological and Non-biological conditions. Bars =S.E.

The time span of the Interrogation times encompass one complete cycle. The virtual target thus represents the expected performance (that is, a perfect "mental tracking"). A phase value of zero represents conventionally the vanishing point of the inducing stimulus. The Biological and Non-biological virtual targets are characterised by different and systematic phase modulations over time. In both cases, this derives from the laws of motion imposed onto the elliptical trajectory.

No statistical difference was found in the average phase of the response between the Biological and Non-biological conditions ($p=0.104$). The interaction SK x IT is close to significance ($p=0.060$). However, by considering only those subjects that maintained central fixation, the interaction SK x IT is statistically significant ($p=0.017$; for free-viewing $p=0.173$).

How well does the imagery process reflect the kinematics of the inducing stimulus? The analysis of the absolute phase error relative to the expected performance shows a significant ($P<0.0001$) phase lag of the response, as compared to the virtual target, in both the Biological and Non-biological conditions. Over one cycle, the average lag is 56.62 ± 29.61 deg. The phase lag increases as the interrogation time increases. Subjects who maintained fixation exhibited a different time-course of the error in the two kinematical conditions ($p=0.030$).

Discussion

Quite surprisingly, even in the case of a biologically moving stimulus, the observed phase of the response is not the one expected for a process following the two-thirds power rule. As a tentative explanation we might surmise that subjects tend to approximate the mental trajectory to a circle. If projected onto an elliptical path, a constant-velocity circular motion would produce a pattern of instantaneous phase which is closer to that produced by a non biological motion over that elliptical path. If the same would occur in the non-biological condition, we would expect the same phase pattern in both the biological and non-biological motion conditions. This turned out to be true as long as the subjects are free to move their eyes during the trial (condition “Free-viewing”). The fact that with central fixation (condition “Fixation”) the pattern of the response is different in the two kinematical conditions, suggests that an inducing stimulus not obeying the two-thirds power law is nonetheless capable of driving, under certain conditions, the time-course of imagery processes.

It is worth recalling that smooth pursuit eye movements are constrained by the two-thirds power law (de’Sperati and Viviani, 1997). Although in the absence of a moving visual stimulus no smooth pursuit eye movements are possible, it is tempting to speculate that, when saccadic eye movements are allowed (Free-viewing condition) a limitation is imposed on visual imagery, resulting in a common pattern of “mental tracking”. Conversely, when eye movements are prevented, the attempt to imagine a non biological motion results in a different pattern of responses. If so, it should be possible to observe the same pattern of eye movements in the biological and the non-biological motion imagery conditions. As a next step, we planned to record spontaneous eye movements associated to this imagery task.

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