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Dynamic Constraints on Haptic Perceptual Judgment of Slanted Surfaces

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Introduction

Most of the times, animals guide their activities in a suitable manner and without incident across the different interactions with their environment. During locomotion, for example, they succeed in both selecting optimal surfaces for supporting their weight and posture and in avoiding obstacles that could prevent locomotion. The term affordance, introduced by J. J. Gibson (1979), defines very well this faculty of the animal to guide behavior by perceiving the action possibilities offered by the surfaces of the environment. The affordance can be defined as the functional utility of an object, a surface or an event for an animal with given physic characteristics (height, weight) and some action capabilities (effectivities) defined according to the species and ontogenetic development.

For Riccio and Stoffregen (1988), stance can be an example of affordance; that is a given environment can afford stance for a given organism. Stance can be defined (as opposed to sitting, leaning against a wall) as any state in which the total mass of the body is supported by the feet. This requires that an axis defined by the body's center of mass and a point within the region of contact with the surface must be aligned with the gravitoinertial force vector. In this state, the body is said to be balanced with respect to external forces. It also requires that the surface must be able to resist the applied force.

The ability of a surface to resist the gravito-inertial force is dependent on its firmness, friction, extent, and inclination (Gibson, 1979; Stoffregen & Riccio, 1988).

Following previous research on the anticipation of capabilities of postural stance (Fitzpatrick, Carello, Schmidt & Corey, 1994; Kinsella-Shaw, Shaw & Turvey, 1992; Klevberg & Anderson, 2002), we have recently evidenced an affordance both in haptic and visual perceptual-motor systems (Regia Corte, Luyat, Darcheville & Miossec, in press). In this study, participants had to determine, by looking or by exploring haptically with a cane, whether a slanted plywood board could support a stable upright posture. In a first experiment, haptic and visual judgments were recorded with ascending and descending methods of limits. Confirming the results found by Fitzpatrick et al. (1994), we could not evidence a difference between haptic and visual thresholds although haptic judgments were achieved by participants who have no particular experience of the cane exploration (sighted participants with occluded vision). Furthermore, a significant positive correlation was found between haptic and visual perceptual thresholds suggesting the presence of amodal information. In a second experiment, two contrasted textures (smooth vs. rough) were used. Results showed a fit between actual and perceptual thresholds and a positive correlation in haptics for rough texture, enlightening a perception of an affordance for postural stance.

The present research is centered around the question of the information involved in haptic judgments which allows the perception of a postural affordance on a slanted surface. When a person moves an arm, or a hand-held object, the arm or the object will resist being rotated along three coordinate systems (x, y, z). Turvey (1996) has perfectly described the biomechanical model which subserves this act (see Figure 1). The forces producing rotation, the torques and the rotational motions measured in terms of angular displacement, velocity, and acceleration vary during the time course of wielding. But these time-dependent forces and motions are linked by the time-independent inertia tensor of the object relative to its fixed rotation point, ordinarily located in the wrist. The inertia tensor, I_{ij} , a 3×3 matrix consisting of moments of inertia (diagonal terms- $i = j$; quantifying resistances to forces tangential to the

Image5rotational motion) and products of inertia (off-diagonal terms- $i \neq j$; roughly, resistances to forces normal to the rotational motion) quantifies the inertia or resistance to be rotated in three dimensions. The specific values of these nine numbers depend on the coordinate system defined at the fixed rotation point. The diagonalized form of I_{ij} is an invariant, independent coordinate-system. For an object, this form is always the same regardless of the coordinate systems at that point through which it is calculated. When the tensor is diagonalized, the products of inertia go to zero leaving only three elements along the diagonal, the eigenvalues I_1, I_2 , and I_3 (where $I_1 \geq I_2 \geq I_3$). The eigenvalues represent the principal moments of inertia with respect to the symmetry axes of the object (the axes about which the object's mass is symmetrically distributed). In fact, the eigenvalues are the maximal moment (I_1) and minimal moment (I_3) for all possible axes through the rotation point and a third moment that tends to be intermediate (I_2).

The symmetry axes correspond to the eigenvectors of the inertia tensor, respectively e_1 , e_2 , and e_3 . These eigenvectors constitute the only nonarbitrary coordinate system, they

are physically determined by the object itself and constitute an intrinsic reference frame. Perception of object magnitude (length for example) has been shown to depend on the eigenvalues of I_{ij} (Solomon & Turvey, 1988) whereas perception of orientations has been found to be linked to eigenvectors (Pagano & Turvey, 1995).

The Inertia Tensor

Figure 1. During the wielding of a hand-held object, the forces producing rotation, the torques (a), and the rotational motions measured in terms of angular displacement, velocity and acceleration (b) vary during the handling. These time-dependent forces and motions are linked by the time-independent inertia tensor I_{ij} (c) quantifying the mass distribution of the object relative to its fixed rotation point, which will ordinarily be located in the wrist (d). The diagonalized form of I_{ij} (e) is an invariant or coordinate-system independent. The eigenvalues I_k are the principal moments of inertia that remain when the products of inertia have been eliminated. The eigenvectors e_k are the directions of the new axes (f). They constitute the only nonarbitrary coordinate system and consequently an intrinsic reference frame. The inertia tensor can be represented geometrically by the ellipsoid of inertia (f) with axes in the directions of the eigenvectors. The distance from the ellipsoid's center to its surface in any direction is inversely proportional to the square root of the moment of inertia about the corresponding axis (Adapted from Turvey, 1996).

Pagano and Turvey (1995) have shown that the perception of the body itself could be based on eigenvectors as does the perception of an object orientation wielded by the hand. The eigenvectors of the arm's inertia tensor naturally coincide with the physical axes of the arm; thus, e_3 coincides with the longitudinal axis of the arm. Pagano and Turvey used asymmetrically weighted splints to break the coincidence of e_3 and the longitudinal arm axis. The asymmetric distribution of the mass shifted the orientation of e_3 away from the axis in a direction and a magnitude dependent on the side to which the mass was placed and on its magnitude and distance from the arm, respectively. In

Pagano and Turvey (1995), e_3 was shifted to the right or left of the arm's longitudinal axis by attaching a 200 g mass 16 cm to the right or left of the arm. Participants had to point the nonvisible arm-plus-splint to a visible target. Rather than pointing at (i.e., aligning the arm with) the target, participants pointed to one side or the other of the target. Error direction and magnitude depended on the direction and magnitude of e_3 . Participants pointed not with the arm itself but with the arm-plus-splint's inertial eigenvector, revealing that felt-arm position was altered by the directional manipulation of e_3 .

Regarding the haptic exploration by a cane, Burton and McGowan (1997) have studied the role of proprioceptive components of haptic probing in judgments of the crossability of gaps. Participants wielded cross-shaped rod parallel to their sagittal planes with a weight attached to one branch of the crossbar, the resulting compound rod was held with the weighted branch above or below the fist. The interest of this paradigm was that the arm-plus-rod system was felt higher (i.e., with more of an angle to the trunk) when the weight was above the fist and lower (less of an angle with the trunk) when the weight was below the fist. Thus, their prediction was that a gap contacted with a smaller perceived angle should feel shorter and should be judged as more crossable, and vice versa for a gap contacted with a larger perceived angle. Results confirmed these hypotheses that crossable gap sizes changed with the perceived arm posture, indicating that the postural information of the arm influenced perceived gap crossability.

The purpose of the present research was to study, with a cross-shaped rod, the role of the arm position in haptic perceptual judgment of a slanted surface for a postural affordance. Contrary to crossable gap judgment which can be achieved with only one joint located on the arm, perception of standable slanted surface involves at least two joints leading to two synchronized movements of the arm: (i) a rotation at the wrist or at the elbow and (ii) a fore-aft movement made possible by a rotation at the shoulder. If the postural information of the arm (i.e., its global perceived orientation relative to the trunk) was involved in haptic perceptual judgments of posturability, that is to say, if the perceived arm posture serves as an angular indicator of the surface inclination, a slanted surface contacted with a smaller angle (weight below the fist) should be felt lower and should be judged as more posturable, and vice versa for a slanted surface contacted with a larger angle (see Figure 2).

MethodParticipants

Six graduate students (3 women and 3 men) with a mean age of 28.5 years ($SD = 6.82$ years) participated in this experiment, five right-handed and one left-handed. They gave their informed consent.

Materials and apparatus

A cross-shaped rod was built by using a cane for blind people of 130 cm and crossbar of 60 cm. An annular weight of 500 g in mass was attached near the end of one branch, placed at 25 cm from the cane. The annular weight could be removed easily allowing to use an unweighted cross-shaped rod. A pair of black occlusion goggles (Quies[®]) and an anti-noise helmet were used.

The apparatus was composed of a grey painted plywood board (100 cm ' 100 cm) strong enough to support a weight of 100 kg which was hinged to a metallic frame. The angle of the board in relation to the ground could be adjusted by means of a motorized

system. A digital spirit level (Bosch DNM 60 L; 60 cm) was fixed on the right side of the plywood board indicating the angular value between the board and the ground. The slant of the board could be adjusted from 0° to 60° in relation to the ground with an accuracy of 0.1° and a very good stability. At 0° of inclination (flat horizontal surface), the board was 12 cm above level of the ground. Consequently, a podium (100 cm $\times$ 150 cm $\times$ 12 cm), of similar plywood and painted in the same grey colour, was placed in the continuity of the adjustable board giving thus a floor on which participant took place (see Figure 2).

Figure 2. Apparatus used in the experiment. As the weighting of the crossbar has an influence on perceived arm posture, the arm will feel higher in the high-weight condition (Left panel) and lower in the low-weight condition (Right panel). If the perceived arm posture serves as an angular indicator of the surface inclination, the angle of the slanted surface should be felt lower and should be judged as more posturable in the low-weight condition and vice versa in the high-weight condition.

Procedure

The task required to determine, by exploring haptically the board with the cross-shaped rod, the critical inclination corresponding to the fall on the slanted surface, that is to say, the critical inclination which would not any longer afford the balance on the surface standing with feet flat (i.e., not on toes) and without bending knees. For the explanation, the apparatus was visible and set at 0° . Participants wielded the cross-shaped rod parallel to their sagittal planes. This rod was held with the weighted branch above (high-weight condition) or below (low-weight condition) the fist. There were three perceptual conditions corresponding to three weight conditions: *high-weight* (HW), *low-weight* (LH) or *no-weight* (control). Participants held the cross-shaped rod with the cane between the third and fourth fingers and were asked not to rotate their hands during the exploration.

The blindfolded participant stood 50 cm away from the slanted surface inside the square marked on the floor with a distance between feet so that legs were parallel to the trunk. The participant in socks was instructed not to move outside the square. The method of adjustment was used for the measure of the haptic perceptual thresholds. Two starting positions for the angular movement of the slanted surface were used: a low position (0°) and a high position (44°) with a rate of $1^\circ/\text{s}$. The order of starting positions was counterbalanced between participants. The experimenter adjusted the inclination of the surface on the starting position required for the current trial (0° or 44°). The participant with his or her dominant hand put the tip of the cross-shaped rod

on the surface and adjusted the inclination of this surface on the critical angle corresponding to the fall. Participants used three verbal indications to move the slanted surface: “more” to increase the inclination of the surface according to the ground, “less” to decrease this inclination, and “stop” to halt the movement. They were authorized to explore the surface during its movement without time restriction. When the adjustment was finished, the experimenter recorded the angular value provided by the digital spirit level. Between trials, the participant remained with the arm at his or her side and the tip of the cross-shaped rod on the floor and waited for the tactile signal (a slap on the shoulder) of the experimenter indicating the start of the next experimental trial. There were six trials (3 with a low starting position and 3 with a high starting position). After which, the same procedure was repeated in the other weight conditions.

Thus, there were three experimental conditions: high-weight (HW), low-weight (LW) and no-weight (control). Each condition was repeated six times (3 low starting positions and 3 high starting positions) resulting in 18 trials for each participant. Orders of presentation of experimental conditions were counterbalanced between participants.

Results

For each participant, a mean perceptual threshold was calculated on the six trials in each condition. The results are depicted in Figure 3.

Figure 3. Mean perceptual thresholds (in degrees) for the fall on the slanted surface as a function of Weight conditions (Low-weight, High-weight, and no-weight) for each participant ($n = 6$). Bars represent SD.

An analysis of variance (ANOVA) with repeated measures on the weight factor (LW, no-weight, HW), on the mean perceptual “fall” threshold (in degrees) revealed that there was a significant effect of weight condition, $F(2,10) = 14.124$, $p < .01$, respectively $M = 26.64^\circ$ for the LW condition, $M = 23.75^\circ$ for the no-weight condition, and $M = 20.93^\circ$ for the HW condition (see Figure 4). A set of a priori non-orthogonal contrasts with Dunnett test revealed that the no-weight (control) condition was significantly different from LW and HW conditions ($p < .05$). Moreover, the analysis of correlations (Bravais-Pearson coefficient) showed that perceptual thresholds for the LW condition were positively and significantly correlated with perceptual thresholds for the no-weight condition ($r =$

.88; $p < .05$). Similarly, perceptual thresholds for the HW condition were positively and significantly correlated with perceptual thresholds for the no-weight condition ($r = .81$; $p < .05$).

Figure 4. Mean perceptual thresholds (in degrees) as a function of weight conditions (Low-weight, High-weight, and no-weight). Bars represent SD.

Discussion

The results showed that the weight position of the cross-shaped rod had an influence on haptic judgments. The pattern of results, consistent with the hypothesis revealed that haptic thresholds followed a linear trend which is due to illusory perceived arm posture provoked by the “haptic prism” of the asymmetrical weighted cane leading to the following means: High-weight (20.93°), no-weight (23.75°), Low-weight (26.64°). Moreover, the presence of significant positive correlations between perceptual thresholds for weight conditions (respectively LW or HW) and perceptual thresholds for the no-weight (control) condition indicated that the weight did not disturb the individual rank of performances as an additive effect. Thus, the perceived postural information of the arm involving the e_3 vector as suggested by previous studies (Burton & McGowan, 1997; Pagano & Turvey, 1995; Turvey, 1996) was also involved in the ability of making haptic perceptual judgments of a postural affordance.

To achieve equilibrium on a slanted surface involves two critical physical parameters: (i) the sliding and (ii) the stability on the board. The sliding on the surface depends of the static friction coefficient (μ_s) which is only tied to characteristics of the two textures (surface and object) in contact independently of the object's weight. The stability depends on the center of mass's projection and it is particularly complex in human in partly due to the multisegmentarity of the body (see Bardy, Oullier, Bootsma & Stoffregen, 2002). The previous experiment we have carried out (Regia Corte et al., in press) has shown that haptic exploration gives accurate information about these parameters but the question remains of how information about sliding and stability is encoded by the haptic system.

The static friction coefficient (μ_s), or potentiality of sliding, could be transferred by tactilo-kinesthetic cues provided by scanning displacements of the cane on the surface which permitted to detect the surface's texture (e.g., its roughness or smoothness) based on parameters as frequency (see Klatzky, Lederman, Hamilton, Grindley & Swendsen, 2003). Secondly, the stability on the surface could depend mainly on

the geometrical properties of the surface as its inclination. The proprio-kinesthetic cues linked to biomechanical properties of the arm during the exploration are a likely candidat to transferring this information. If this experiment has confirmed the role of proprio-kinesthetic cues in haptic judgments of an affordance, further experiments are required to clearly evidence the complementary of these two haptic cues.

Moreover, as pointed by Fitzpatrick et al. (1994), there is a gradient in the haptic information which could differentiate surfaces of different slants. Indeed, as the cane drawn down the surface (with the elbow joint kept stiff for simplicity), the angle between the cane and surface, as well as the angle at the wrist, changes. The pattern of change (or its rate) differs for the steep and flat surfaces. Consequently, future experiments will be designed to isolate these two informational categories (angle to the trunk vs. time-dependent pattern of change) in order to determine their respective importance in this perceptual task.

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ABSTRACTS

The purpose of this present research was to study the role of the arm perceived position in haptic perceptual judgment of a slanted surface for a postural affordance. Participants wielded a cross-shaped cane parallel to their sagittal plane. This cane was held with a weighted branch above (high-weight condition) or below the fist (low-weight condition). The task required participants to determine, by exploring the surface with the cross-shaped cane, the critical inclination corresponding to a fall on the slanted surface. Three weight conditions, high-weight (HW), low-weight (LH) and no-weight (control), were used to change the perceived orientation of the arm and thus evaluate the role of this postural information. Results showed an effect of the weight factor with a pattern of results consistent with the assumption that postural information of the arm was involved in haptic perceptual judgment of posturability on a slanted surface.

L'objectif de cette expérience est d'étudier le rôle de la position perçue du bras dans la perception haptique d'une surface inclinée pour une affordance posturale. Les participants explorent la surface avec une canne en la tenant parallèle à leur plan sagittal. Le pommeau présente un segment perpendiculaire à l'axe principal de la canne (croisillon) qui peut être chargé d'un poids supplémentaire. Ce poids se trouve au dessus (condition « poids en haut ») ou en dessous (condition « poids en bas ») du poing. La tâche consiste à déterminer, en explorant la surface avec la canne et sans faire réellement l'action, l'inclinaison critique correspondant à la chute sur cette surface. Trois conditions perceptives (*poids en haut*, *poids en bas* et *sans poids*) sont utilisées afin de modifier la perception de la position du bras et permettre ainsi d'évaluer le rôle de l'information proprioceptive du bras. Les résultats révèlent une modification significative du seuil perceptif critique en fonction de la place du poids au niveau du pommeau. Cet effet est compatible avec l'hypothèse selon laquelle l'information proprioceptive du bras est impliquée dans ce jugement haptique relatif à l'équilibre postural sur une surface inclinée.

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