Tactile perception and virtual guidance of movement: from clinical to artistic applications

Francis G. Lestienne\(^1, 2, 3\), Francine Thullier\(^1, 2, 3\), Marie-Charlotte Lepelley\(^1, 3\)

Université de Caen Basse-Normandie
1ERT 2002 Rapsodie
2EA 4260 Information, Organisation et Action
3Modesco UMS CNRS 843

Recent studies have demonstrated the efficiency of a vibrotactile device “Tactile Compass” in guiding the hand in a pointing task during a blind experiment. Based on this work, the introduction of tactile information is proposed in terms of tactile semantics, which is a promising avenue towards better support for man-machine communication in various areas: land navigation guidance, clinical applications such as rehabilitation, and artistic applications such as dance creations.

De récentes études ont démontrées l’efficacité d’un dispositif constitué de vibrateurs tactiles (“Boussole Tactile”) permettant le guidage de la main dans une tâche de pointage en aveugle. Sur la base de ces travaux, il a été proposé que l’introduction des informations tactiles, en termes de sémantique tactile, dans la communication homme-machine est une ouverture très encourageante pour des domaines variés : guidage pour la navigation terrestre, applications cliniques telles que la rééducation et applications artistiques telles que la chorégraphie.

Introduction

An anatomical structure comprising hundreds of segments connected by over eight hundred muscles makes the human body a very complex organism indeed. This complexity provides the polyarticular chain with the mechanical underpinning for postural stability and a host of different, coordinated movements whose virtuosity, skill and elegance are ensured by the sophisticated flexibility of a plurimuscular system [LES 88] [LES 97]. The core question remaining is how the nervous system (NS) reconciles control of motor activity expressed in three-dimensional space with the existence of the pull of gravity [LEST 88b] [LES 02]. This fundamental question generates and fuels constant debate, to which biomechanics and neurophysiology have their own contribution to make.
However, this domain cannot be approached purely in terms of the motor aspect [BON 03]. The perceptual side is of necessity an integral part of any theoretical/experimental approach to the production of movement [LES 01]. It should be briefly pointed out that for organising the positioning or movement of the bodily segments in space the NS is endowed with specialised interfaces between the organism and the external world: the sensory receptors [LES 02b] [LES 03].

Four main families of such receptors (Figure 1) can be described [PER 94]. The visual sensor (1) provides information on the structure and topography of the outside world, while its peripheral retina also makes it an excellent detector and analyser of optical flow [LEJ 06] [LES 77]. The head’s movements in space can be detected both by the visual system and the vestibular sensors 1 situated in the inner ear (2), which in combination form a gravito-inertial focal point that reacts to angular and linear movements of the head. The movements of the bodily segments and, consequently, articular rotations and variations in the length and strength of muscles are measured by proprioceptive sensors 2 (3 a, b, c). Finally, the tactile sensors (4) situated at skin level also contribute to mechano-sensitivity in responding to deformations of the dermis caused by pressure or friction.

---

1. Vestibular receptors, often described as the balance receptors, comprise two structures: the otolithic organs which detect linear acceleration of the head; and the semicircular canals that detect angular acceleration of the head.

2. Situated in the musculoskeletal system: muscle (muscle spindle 3a), articulation (joint receptor 3b) and tendon (Golgi tendon organ 3c). Proprioceptive and vestibular sensitivity contribute to kinaesthetic sensitivity (Gk. kinesis, “movement”) which provides the brain with information regarding movement, position, the strength of the various bodily segments and bodily orientation.

---

Fig. 1. The four main families of sensory receptors involved in the control of posture and movement (adapted from [PER 94]. Visual (1), vestibular (2), and proprioceptive (3) and tactile (4). See explanation in the text).
1 Complementarity of sensory information

It should not be forgotten that as early as 1902 French mathematician Henri Poincaré [POI 68] pointed out in his philosophical writings – and in particular in *Science and Hypothesis* – the role of movement in the genesis of our notion of space. For Poincaré, *while movements take place in three-dimensional space, it is not necessary to represent them in this space, but only to represent the physical sensations accompanying them*. These sensations thus play a predominant part in the construction of a space that would never have come to exist without them. In his analysis of the role of *visual impressions*, Poincaré demonstrates that visual space is only a part of space and that true space is *motor space*, and that experience has taught us that it is convenient to ascribe three dimensions to space.

Regarding the vestibular sensors needed for our sense of direction, it is clear that these organs exist to warn us of changes taking place in the external world – to detect acceleration due to movement and rotation of the head – and not to warn us that space is three-dimensional. Through integration of information at neuronal level we deduce the orientation of our head. Nonetheless, these sensations teach us nothing about the movements of the torso and limbs relative to the head, nor about the changes of position the latter can undergo. Thus there is a patent need for complementarity between the muscular and vestibular sensations [LEJ 04] associated with the tactile ones [KAV 08].

In this context, Poincaré assumed that adequate perception of the orientation of the body in the environment is based on the integration of signals from different sensory systems. As a consequence, deficits in this integration may cause results in substantial errors in the perception of body orientation.

This hypothesis was confirmed in studies of the control of posture in weightlessness [CLE 84], [LES 88]. In these experiments, astronauts wore a head-mounted optical device in which they could see a non-structured surface stabilized in respect to the head. Thus, based on vision, they could not detect the orientation of the body in the space station. When asked to “stand vertically” to the floor with their feet attached to it, astronauts leaned the body forward by more than 30 deg, while reporting that their body is perpendicular to the floor. In weightlessness, the vestibular system is dysfunctional and its afferent output may not be used to identify the vertical direction. Tactile perception from the feet is also distorted compared to that elicited by the body weight during standing on the earth. Therefore, natural visual, vestibular, and tactile clues allowing one to identify the vertical direction on the earth were not available in these experiments. EMG analysis had shown (fig 2) that, rather than relaxing leg muscles, astronauts actively specified the posture that they consider vertical. During standing on the earth, the activity of ankle extensors dominates over flexor activity [CLE 84] whereas in weightlessness, the activity of ankle flexors becomes dominant. With adaptation to weightlessness, the deviation of the body from the vertical to the floor of the spaceship progressively decreased, and the body orientation and the projection of the body’s centre of gravity approach those observed during standing in normal weight condition on the earth (Figure 2); [LES 88].

Complementarity of sensory information is necessary not only for correct perception of the posture but also for an internal representation of the body geometry called the *body scheme* [HEA 11]. Adrian [ADR 47] suggested that the body scheme is internally represented in relation to the external world. More recently, in his book *Descartes’Error*, Damasio in 1994 [DAM 99] paraphrased the same idea: “the body, as represented in the brain, may constitute the indispensable frame of reference for the neural processes that we experience as the mind…”. He also suggested that in the domain of human action “the body is used as a yardstick”.

Schedae, 2010, prépublication n° 4 (fascicule n° 1, p. 49 -58).
There are several studies favoring the existence of an internal body scheme that is preserved as a coherent whole in changing external conditions. In particular, it has been shown that when asked to draw ellipses in different planes during the flight in a spaceship, subjects orient them in relation to the longitudinal axis of the body \[GUR\ 93\], \[LIP\ 02\], regardless of the orientation of the body in the environment. The interpretation of complex tactile stimuli on the body surface is also preserved in these conditions and the stimuli are correctly identified in relation to the longitudinal axis of the body \[GUR\ 93b\].

2 Sensory substitution and tactile information

Another significant aptitude of the NS has to do with the existence of sensory substitution, related to the brain’s extreme plasticity. Indeed the brain is able to use information from an artificial receptor in place of that usually transmitted from an intact sense organ \[BAC\ 96\]. The classical illustration of sensory substitution is provided by the Braille system, which allows the blind to read by replacing visual with tactile information.

Advances in the instrumentation technology of sensory substitution have presented sophisticated tools for compensation of sensory loss such as sight function. One of the most well known form of sensory substitution devices was Bach-y-Rita’s TVSS (Tactile Vision Substitution System) that converted the image from a video camera into a tactile image and coupled it to the tactile receptors on the back of his blind subject. \[BAC\ 69\].

Numerous studies of the sensitivity of tactile receptors to vibration have shown that low-level mechanical vibration is a particularly effective stimulus for activation of the cutaneous mechanoreceptors sensitive to mechanical deformations of the skin. Experiment using “vibro-tactile matrix” has shown that subject can perceive complex tactile stimuli such as
as letters and digits [LEP 05], [LEP 08]. The task of interpretation of these tactile images, applied to different skin areas under varied condition was not affected by the absence of the gravitational vertical, although this task is closely associated with mechanisms for the perception of body configuration, as well as the spatial orientation of the different body parts [GUR 93b].

Specific role of information of plantar tactile origin in posture control has been demonstrated in respect of the sole’s front and rear contact points [AND 88], [KAV 99], [KAV 01], [ROL 02]. In association with kinaesthetic – vestibular and proprioceptive – information, the tactile mode plays a specific part in fine posture control [AIM 07] and so contributes to the construction of the subjective vertical, which itself becomes decisive in orientation control when visual perception of the vertical has been disturbed [MIT 86].

While tactile receptors appear in the examples just quoted as a sensory modality working with the vestibular, proprioceptive and visual systems in perception of bodily orientation, the same receptors can also, after a learning process, play a part in cognitive operations involving recognition of forms.

3 The tactile compass

Our studies [LEP 05], [LEP 08] [LEP 09] have enabled us to establish the technological and methodological foundations for an instrument for guiding – or assisting – movement which draws on the tactile sensory modality springing from the cutaneous mechanoreceptors. The capacities of these tactile receptors in terms of spatial and temporal encoding are linked to the extreme sensitivity, acuity and rapidity of our processing of tactile signals [CHO 00] [CHO 03] [SHI 73] [SKL 99]. On the basis of this cutaneous sensitivity we had the idea of making use of tactile encoding provided by a matrix or “tactile compass”, a device made up of vibrotactile microstimulators placed on the surface of the skin and delivering tactile messages intended to guide movement and aid terrestrial navigation.

The vibrotactile device (Caylar Society ©) (Figure 3) consisted in 49 microvibrators (called “pins”) laid out in a 7x7 matrix, a battery, a micro-controller and a connector serial port. The 49 microvibrators contained inertial vibrators activated by micromotors (diameter: 2 mm). The distance between each vibrator was 6 mm. The oscillation frequency of the pins was 50-60 Hz with a magnitude of 2 mm. The tactile messages were provided in a dynamic way by the successive activation of each pin.

![Fig. 3. Two types of tactile compass: “compact” on the left and “distributed” on the right, allowing for configuration according to anatomical localisation.](image-url)
From the work using the Caylar’s vibrotactile device it has emerged that the subjects had a highly developed ability to recognise “tactile forms” and “tactile images”. The most significant shaping factors in these studies have a character that is distinctive in terms of two notions: those of tactile semantics and perceptual learning.

Tactile semantics results from structural representations recognisable not by their (static) shape, but by a specific pattern of (dynamic) movement of points of vibro-tactile stimulation applied to the skin. The movement of these points thus forms a mnemonic tactile trace suggesting the appropriate physical action in the light of a set of tactile prescribers:

– directional: left, right, high, low, forward, back, etc.
– cinematic: advance, halt, accelerate, slow down, etc.
– kinesiological: ascend, descend, turn, etc.

Perceptual learning results from cerebral plasticity in the cognitive processing of tactile encoding. This means that learning is facilitated by the implementation of learning procedures. Input from new technology – virtual and augmented reality – will assist the development of original cognitive protocols allowing for the enhancement of perceptual learning.

4 Applicative programs

Recent studies investigated the efficiency of the Caylar’s vibrotactile device to guide the hand in a pointing task in a blind experiment. The performances obtained using tactile coding establish the fact that tactile information transmitted via our vibrotactile device is involved in the processes of to control movement in tridimensional space [LEP 09]. Based on this work, it is clear that introduction of tactile information is a promising avenue toward better supporting human-machine communication in various domains such as navigational spatial guidance, rehabilitation, handicap and the artistic community. The applicative aspects are managed by the ERT 2002 “Rapsodie” a Technological Research Team at the University of Caen Basse-Normandie 3. Backed by Caylar, the industrial partner, the team works with two university hospital partners 4 and a partner of the world of culture 5.

4.1 Land Navigation

Several studies have demonstrated the usefulness of tactile modality in multi-task situations: land navigation [DUI 05], [ELL 06], Vehicle navigation [ROC 00], [VAN 03], [VAN 04], awareness, attention [RAJ 00], [SHI 73]. Likely advantage of tactile guidance we have examined the feasibility and the effectiveness of tactile interfaces using patterns of vibratory code for land navigation. In this context, the ERT 2002 initiated an advanced technology program (Exploratory and Innovative Research 6) to develop tactile assistance in navigation on earth in a hostile environment by means of a “tactile compass” made up of a matrix of micro-vibrators, that reproduce tactile encoding on skin surface to orient the wearer (Figure 4).

3. www.unicaen.fr/recherche/mrsh/rapsodie
4. The Montreal Rehabilitation Institute (affiliated with the University of Montreal) and the Jewish Rehabilitation Hospital (affiliated with McGill University).
5. CDA 95 fr. Enghien-les-Bains Art Centre.
6. REI 08 C0001 (Délégation Générale à l’Armement).

4.2 Rehabilitation

We are involved in various projects dealing with sensorimotor rehabilitation after neurological injury affecting the control of equilibrium and/or the functional abilities in limb coordination. Tactile sensorial modality and cerebral plasticity are the most salient elements that form the context of this project and that allow development of rehabilitation techniques combining the tactile matrix and virtual reality techniques.

The core instrumentation is the “tactile compass”, integrated in the he AMOSIT plateform (Motor Function Assistance through Tactile Sensitivity) that send messages from the movement sensors. The AMOSIT plateform can have a dual function: assistance in guiding gesture and assistance in guiding verticality (Figure 5).
4.3 Verticality and tactility, new fields of artistic research

Taken in conjunction with the latest technological developments of the “Tactile compass”, our academic work in relation with the clinical projects means we can foresee new modes of interaction and communication between art and fundamental science with applications in the field of sensory handicap. In one instance the application of the academic research to dance and new technology, in combination with our studies on the guidance of movement with a “tactile compass”, has found concrete expression in dance works written with the Pedro Pauwels company.

Sens 3 or “Verticalité et Tactilité” is a performance you discover barefoot. In his exploration of the domain of the sensory, Pedro Pauwels seeks to make tangible movement that must reconcile the force of gravity with the maintaining of bodily balance. In Sens 3 movement sensors attached to the performers’ bodies send the audience real-time tactile information on the dancers’ “verticality”. Reception of the information is effected by a system of vibrators set in a “tactile cushion” under the spectators’ feet (Figure 6). Sens 3 thus sets up a tactile communication between performers and spectators which in a way resembles the sign language of braille, the semantics of which – admittedly very limited – could be likened to kinesiological prescribers such as lean, turn, crouch, etc.

---

Fig. 6. Sens 3 “Verticality and Tactility is a choreographic work you discover barefoot.” Motion sensors on the dancers’ bodies provide spectators with real time tactile information on the dancers’ “verticality”. This is done using tactile cushions placed under the spectators’ feet.

---

7. A partnership agreement signed between the University of Caen and the Enghien-les-Bains Art Centre in 2007 enhances the already close links between art and science via choreographic experiments using the potential of new technology to influence the non-visual perception of the body in movement.

8. Francis G. Lestienne and Pedro Pauwels, a choreographer, have set out to make the public share “augmented perceptions”. Between the two there sprang up a fruitful collaboration involving two forward-looking adaptive dance works, Sens 2 and Sens 3. In Sens 2 the muscle melody of the dancing body generates a non-visual perception of that body via a “recording of its internal noise” – in this case the electromyographic (EMG) activity of the muscles. The sounds obtained are then incorporated into a musical score for the dance piece. Sens 2 enables transcendence of the visual art of dance by using a sound-based “visibility” of gestural poetry to render it complementary. The digitised EMG signals are transformed in real time into sound signals allowing for the upsurge of muscle melodies shot through with “internal emotion”; these melodies can then be perceived by the spectator via the other perceptual channel of hearing.
References


[LEP 08] LEPELLEY M.C., “Production du geste dans l’espace tridimensionnel/mouvement dansé au gui-


[LES 02] LESTIENNE F.G., THULLIER F., “L’orientation du mouvement et de la posture dans l’espace tridi-


[VAN 03] VAN ERP J.B.F., VAN VIEEN H.A.H.C., “A Multi-purpose Tactile Vest for Astronauts in the Interna-