SEVENTH FRAMEWORK PROGRAMME

"Ideas" Specific programme

European Research Council

ERC Advanced Grant

Grant agreement for Advanced Grant

Annex I - "Description of Work"

Project acronym:	PATCH
Project full title:	Computational Theory of Haptic Perception
Date of preparation of Annex I	November 16, 2009
Date of Update (in view of one year no-cost extension)	June 05, 2015
Principal Investigator	Vincent Hayward
Host Institution for the project	Université Pierre et Marie Curie (UPMC)
Other Beneficiaries:	Centre National de la Recherche Scientifique (CNRS)
Contract number:	247300

Table of Contents

i. Scientific Leadership Profiles

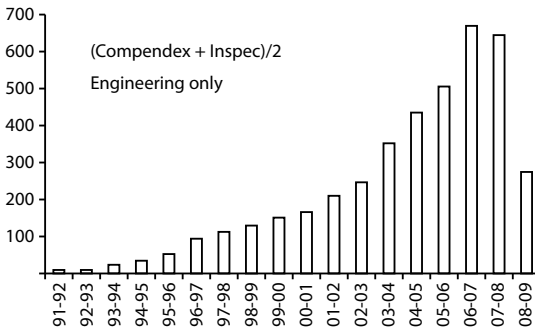
In the past 15 years, the applicant has mostly dedicated his research to the concept of haptic interface—yet not entirely; he has also cultivated an activity in systems and controls. Haptic technology aims at artificially causing the sensation of touching objects. By analogy, computer graphics aims at causing the sensation of seeing objects. There are many applications of "haptics". Haptic technologies now contribute to teaching, training, remote medicine, surgical planning, rehabilitation and therapy as well as to surgical aids: *minimally invasive surgery* has created new challenges due to the diminished sensory feedback to the surgeon. With haptic technology, tactile feedback can be restored, thereby improving the technique and patient outcome. In manufacturing, haptic technologies are now applied to design and assess products and processes without physical mockups. An application which the applicant is pursuing is assist the blind and visually impaired access graphical information.

Since the applicant spent—until now—his career in Canada, it is fair to evaluate it in this context. In Canada, research funding is driven by the notion of individual grants, the so-called "Discovery Grants" of the Natural Sciences and Engineering Council. They are designed to track the career of the researchers in cycles of four or five years and are awarded by peer committees after rigorous scrutiny of the applicants' progress and result in increase or decrease of operating funding. The titles of my discovery grants in the past 10 years were: *High Performance Robotic Devices* (95-99), *Advanced Human-Machine Interfaces* (99-03), *High Fidelity Haptics* (03-07), and now *Physically and Perceptually Based Haptics* (07-11). These cycles reflect a strategic progression from the acquisition of mastery in technical topics relevant to haptics to the application of this mastery to the investigation of biological problems. Since I have now moved to UPMC from McGill University, I will have to relinquish this funding in the near future.

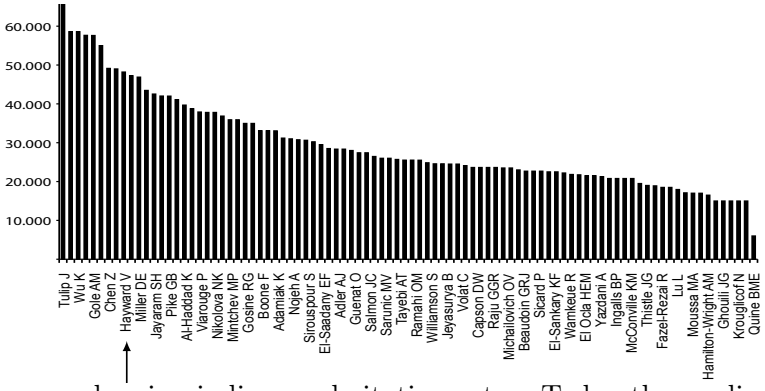
The applicant's long term objective is to develop knowledge about the haptic channel in humans and use it to develop interfaces. The applicant develops new types of stimulators that are increasingly capable and use them to explore how people use their haptic channel to act and sense and how this channel might be working. My approach relies on a reciprocal relationship between these two activities, creating a virtuous circle. The resulting discoveries, in turn, show how to make better devices, spinning off applications. These results were acknowledged by several communities in the form of a research prize (Canadian National Institute for the Blind), keynote lectures and an average of five invited lectures per year, four best papers awards (ACM, IEEE) and one best demonstration award. V. Hayward was invited to contribute chapters to two new textbooks on haptics, one edited by Prof. Ming Lin from the University of North Carolina targeted at a computer graphics audience (ACM), and the other by Prof. Martin Grunwald of the University of Leipzig: *Human Haptic Perception: Basics and Applications* (Springer). I was invited to contribute a survey article for the journal *Brain Research Bulletin*, two tutorials for the IEEE *Robotics and Automation Magazine* and one entry for *Scholarpedia*.

Besides the invention and the design of several novel and highly effective tactile and haptic transducers, the applicant's technical contributions can also be described by the development of the concept of "haptic synthesis", a collection of algorithms intended to reduce the amount of online computations to a small and predictable amount, yet able to synthesize haptic signals which are physically accurate, including the cases of dynamic behaviors including viscosity, plasticity and creep. For a summary, see (Hayward, 2007, CV page 5). The applicant's scientific contributions are the identification and the demonstration of a set of distinct "haptic cues" which have a conceptual analogy to the perceptual cues known in audition and vision. The cues that me and my collaborators have identified defy simple deductions. What they show is that the perception of a shape is *indirectly* related to the effects of touching a solid shape. He has shown that forces fields experienced by subjects—determining their motor activity—provide the perception of shape independently from proprioceptive information (Robles-De-La-Torre and Hayward, 2001, CV page 5). He has determined that the orderly displacement of contact on the finger provided the sensation of shape, also without proprioception, and has demonstrated classes of tactile 'equivalent stimuli' where different types of skin deformation gave rise to the same perception of shape (see Hayward, 2008a, 2008b for a survey, CV page 5). It is the object of this proposal to bring this research to a completely new level of generality.

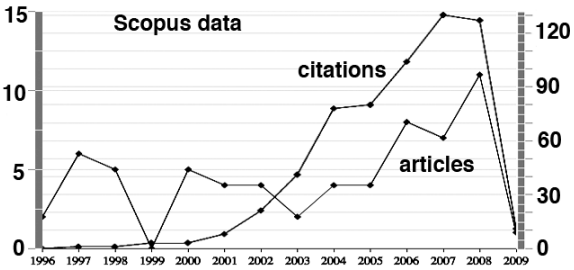
To summarize the applicant's activity in statistical form, please first consider that 15 years ago, "haptics" was a very small field as seen on the right. This graph shows the yearly number of articles published with the word "haptic" in the title (Engineering only). Today haptics has become a recognized field with its industry, its science and is well represented in several communities (Robotics, Systems and Control, Neuroscience, Psychology) has its transactions in the IEEE and two major conferences. It is still a small field compared with, say vision in all its aspects, but is growing fast.

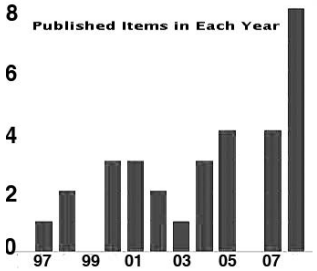


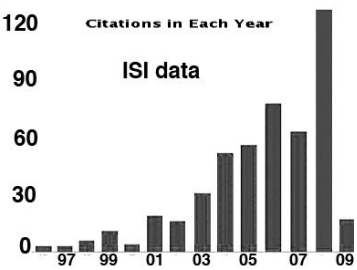
We then look at the applicant's performance within the Canadian system using the histogram of the funding of researchers ranked by my committee (20% of the whole population in my area) and where it can be further shown that better funded colleagues are all more senior. It can be reliably be concluded that he ranks in the upper 10% of Canadian researchers in the broad area of electrical systems.



We can now look at the impact of his research using indices and citation rates. Today the applicants's 'h-index' is 15 according the Scopus data-base and 14 according to the ISI data-base (it was 9 when he prepared his dossier for his new position, spring '08). There is therefore growing interest in his work, now exceeding 130 citations a year, and the growth of citations is much higher than the growth of his production. It can be further concluded that his work has impact much outside Engineering.







V. Hayward maintains strong ties with industry. Immersion Canada Inc. and Nokia Corp. were contributing in cash to his research. He is one of the co-founder of Haptic Technologies Inc., Montréal, Canada, acquired by Immersion Corp in 2 000 ($7M US) to become Immersion Canada Inc.[1] MPB Technologies Inc markets the Freedom-6/7 haptic device that he conceived in 1998.[2] He worked with VisuAid Inc, Québec, until it merged with the HumanWare group of New Zealand. He has done consulting for Intuitive Surgical Inc. the maker of the DaVinci surgical robot, which licensed one of his inventions. He has not neglected communications with a larger public with interviews in science programs, three mentions in the *NewScientist* and a prominent feature in the journal *Nature* entitled the "Big data: The next Google" where the leaders of emerging areas were interviewed (*Nature* 455, 8-9 (2008), doi:10.1038/455008a). In the past 10 years he has supervised two Post-Docs, 10 PhDs and 10 Masters who found for 1/3 careers in academia and for 2/3 in industry. He has always attracted a steady stream of award-winning students and now looking forward to building a new team at UPMC.

This section may be closed by quoting an anonymous referee in a recent competition: "His work is consistently characterized by relating problems of current interest to fundamental physical and mathematical principles. He and his students have done better than anyone in the field and I think this is the source of his excellent accomplishments."

The applicant has been delayed by severe pneumonia in 2003.

[1] http://www.immersion.com/about/contact/

[2] http://www.mpb-technologies.ca/mpbt/haptics/hand_controllers/freedom/description.html

Curriculum Vitae (Hayward)

1. Positions

81-83 Visiting scholar, Purdue University, Indiana, USA, School of Electr. Eng.
83-85 Chargé de Recherche, CNRS, LIMSI, Orsay.
85-89 Adjunct Professor, Department of Electrical Engineering, McGill University, Canada.
89-94 Assistant Professor, Department of Electrical Engineering, McGill University, Canada.
94-06 Associate Professor, Dept. of Electrical and Computer Engineering, McGill University, Canada.
01-04 Director, Center for Intelligent Machines, McGill University, Canada.
06- Professor, Dept. of Electrical and Computer Eng., McGill University, Canada. (on leave)
06-07 Professeur invité, Université Pierre et Marie Curie.
08- Professeur associé, Université Pierre et Marie Curie.

2. Funding (On-going and recent)

10-14 The Hand Embodied, 7th Framework Programme on Research, Integrated Project IP, A. Bicchi (Coordinator), P. van der Smagt, K. J. Kyriakopoulos, D. Prattichizzo, A. M. L. Kappers, V. Hayward, M. O. Ernst, H. Jörntell, M. Nilsson (PIs). Funding: 118 of 1,794 k€/year. *There is some relationship with the present* ERC *project in terms of device development but there is no conceptual nor budgetary overlap since Hayward's contribution to "The Hand Embodied" has no theoretical component. However, the inclusion of A. M. L. Kappers and M. O. Ernst in the consortium is highly beneficial since they are listed as collaborators in the* ERC *project.*

08-11 Natural Interactive Walking, 7th Framework Programme on Research, Technological Development STREP, F. Fontana (Coordinator), J. Cooperstock, S. Serafin, A. Lécuyer, V. Hayward (PIs). Funding: 106 of 391 k€/year. *No conceptual nor budgetary overlap with the* ERC *project.*

08-12 Physically and Perceptually Based Haptics, Discovery Grant, Natural Sciences and Engineering Research Council of Canada (NSERC), V. Hayward, $48,200/year.

06-09 The design of Multi-Modal Information Displays. Collaborative Research and Development Grant. Natural Sciences and Engineering Research Council of Canada (NSERC),V. Hayward, J. J. Clark & K. E. MacLean, $57,600/year plus industry contributions ($36,225/year cash, $40,000/year in-kind). Completed.

06-09 Informatisation du graphisme tactile l'usage des personnes aveugles ou handicapes visuelles. Group grant. Fonds québécois de la recherche sur la nature et les technologies (FQRNT), V. Hayward, A. Dufresne, N. Trudeau. $42,000/year. Completed.

06-08 Sound and Interaction in the Design of Enactive Interfaces. Special Research Opportunity - Research Project, Natural Sciences and Engineering Research Council of Canada (NSERC) M. Wanderley, V. Hayward, S. McAdams, Ph. Depalle, G. Scavone, and C. Guastavino, $272,000, $207,000. Completed.

05-08 High Fidelity Surgical Simulation. Collaborative Research and Development Grant. Natural Sciences and Engineering Research Council of Canada (NSERC), V. Hayward, $51,000/year plus industry contribution ($17,000/year cash; $20,000/year in-kind plus equipment). Completed.

3. Supervision (past 10 years, subsequent position)

07-09 Mounia Ziat, Post-doc, now at Wilfrid Laurier University.

04- Hsin-Yun Yao, Ph.D. on-going (delayed for family reasons).

04-09 Gianni Campion. Ph.D. The synthesis of three dimensional haptic textures, geometry, control, and psychophysics, Post Doctoral Fellow, Boston University.

04-09 Andrew H. Gosline, Ph.D. Haptic Synthesis of Dynamically Deformable Materials. Post Doctoral Fellow, McGill University.

03-09 Vincent Levesque, Ph.D. Virtual Display of Tactile Graphics and Braille by Lateral Skin Deformation, (combined M.Eng then Ph.D.). Post Doctoral Fellow at the University of British Columbia.

03-08 Jerome Pasquero, Ph.D. Tactile display for mobile interaction. Scientist, Research In Motion Inc.

02-07 Qi Wang, Ph.D. A Biomechanically Optimized Tactile Transducer and Tactile Synthesis. Post Doctoral Fellow, Biocontrols Laboratory, Harvard University.

99-01 Gabriel Robles-de-la-Torre, Shape Perception By Touch. Scientist. Founded the International Society for Haptics, http://www.isfh.org/

99-02 Mohsen Mahvash, Ph.D. Haptic Rendering of Tool Contact And Cutting. Post Doctoral Fellow at John Hopkins University.

98-02 Dingrong Yi, Ph.D. Computer Aided Display of 3D Angiograms, Using Graphics and Haptics. Scientist, Sunnybrook and Womens College Health Science Center.

97-01 Erick Dupuis, Ph.D. A General Framework For the Manual Teleoperation of Kinematically Redundant Space-based Manipulators. Scientist, Canadian Space Agency.

96-00 Oliver R. Astley, Ph.D. A Software Architecture For surgery Simulation Using Haptics. Scientist, GE Central Labs.

4. Appointments with Agencies

07-08 Grant selection panel member European Commission Program "Information Society and Media Directorate, Cognitive Systems and Robotics".

05-08 Member of "Conseil Scientifique, Direction des recherches technologiques du Commissariat lnergie atomique (CEA)," France.

94-05 Three time leader of national projects of the Institute for Robotics and Intelligent Systems (IRIS a federal Network of Centres of Excellence): 02-05: Foundations of Haptic Interfaces for Virtual Environments and Communications; 98-02: Haptic Interfaces for Virtual Environments and Communications; 94-98: Haptic Interfaces for Teleoperation and Virtual Environments.

04-07 Member of NSERC Grant Selection Committee GS-21 (Interdisciplinary).

03-09 Member of the College of Reviewers, Natural Sciences and Engineering Council of Canada (NSERC), Special Opportunity Program.

00-09 Member College of Reviewers, Canada Research Chairs Program.

99-02 Elected member PRECARN-IRIS (NCE) Research Management Committee.

95,00 Panel member of the Robotics Program, National Science Foundation, Washington DC, USA.

5. Referee Appointments for Journals

ACM T. on Applied Perception; ACM T. on Human-Computer Interaction; Advanced Robotics; ASME J. of Biomechanical Engineering; ASME J. of Dynamics, Measurement and Control; ASME J. Mech Design; Automatica; ASME J. of Computing and Inf. Sci. In Eng.; Control Engineering Practice; Experimental Brain Research; Haptics-e; IEEE T. on Automatic Control; IEEE T. on Automation Sci. and Eng.; IEEE T. on Control System Technology; IEEE Computer Graphics and Applications; IEEE Trans. on Computer Graphics and Visualization; IEEE T. on Haptics; IEEE/ASME T. on Mechatronics; IEEE T. on Neural Syst and Rehab. Eng.; IEEE T. on Robotics [and Automation]; IEEE T. on Speech and Audio Processing; IEEE T. on Pattern Analysis and Machine Intelligence; IEEE Trans. on Systems, Man, and Cybernetics; IEEE T. on Biomedical Engineering; IEEE T. on Ultras., Ferroelectrics, and Freq. Control; International J. of Control; International J. Robotic Research; Journal Européen des Systèmes Automatisés; J. of Computing & Information Science In Engineering; Journal of Computer Science and Technology; The Journal of Experimental Biology; Journal of Neuroscience (Methods); Journal of Systems and Control Engineering; Mechanisms and Machine Theory; Medical Image Analysis; Medical Engineering & Physics; Measurement Science and Technology; Perception; Attention, Perception and Psychophysics; Presence; Revue canadienne de génie électr. et de génie infor.; Robotica; Sensors and Actuators A (Physical); Springer Verlag Publications; Springer Virtual Reality Journal; Technique et Science Informatiques; T. on Industrial Electronics; Virtual Reality;

10-Year-Track-Record (additional information at http://www.cim.mcgill.ca/hayward/)

1. Top 10 publications (out of 30, [citation count] from Scopus)

Wijntjes, M. W. A., Sato, A., Hayward, V., Kappers, A. M. L. 2009. Local Surface Orientation Dominates During Haptic Curvature Discrimination. IEEE *Transactions on Haptics*. 2(2):94-102. [1]

Carter, O., Konkle, T., Wang, Q., Hayward, V., Moore, C. I. 2008. Tactile Rivalry Demonstrated with an Ambiguous Apparent-Motion Quartet. *Current Biology*, 18(4):1050-1054 [4]

Hayward, V. 2008a. A Brief Taxonomy of Tactile Illusions And Demonstrations That Can Be Done In a Hardware Store. *Brain Research Bulletin*, 75:742-752. [5]

Wang, Q., Hayward, V. 2007. In Vivo Biomechanics of the Fingerpad Skin Under Local Tangential Traction. *Journal of Biomechanics*. 40(4):851-860. [7]

Mahvash, M. and Hayward V. 2005. High Fidelity Passive Force Reflecting Virtual Environments. IEEE *Transactions on Robotics and Automation*. 21(1):38-46. [36]

Hayward, V., Astley, O. R., Cruz-Hernandez, M., Grant, D., and Robles-De-La-Torre, G. 2004. Haptic Interfaces and Devices. *Sensor Review*. 24(1):16-29. [42]

Dupont, P., Hayward, V., Armstrong, B., and Altpeter, F. 2002. Single State Elasto-Plastic Friction Models. IEEE *Transactions on Automatic Control*. 47(5):787-792. [81]

Robles-De-La-Torre, G. and Hayward, V. 2001. Force Can Overcome Object Geometry in the Perception of Shape Through Active Touch. *Nature*. 412:445-448. [65]

Cruz-Hernandez, J. M. and Hayward, V. 2001. Phase Control Approach to Hysteresis Reduction. IEEE *Transactions on Control Systems Technology*, 9(1):17-26. [62]

Janabi-Sharifi, F., Hayward, V., and Chen, C-S. J. 2000. Discrete-time Adaptive Windowing for Velocity Estimation. IEEE *Transactions on Control Systems Technology*. 8(6):1003-1009. [47]

2. Five Monographs and Chapters in Books (out of 9, [citation count] from GoogleScholar)

Hayward, V. 2008b. Haptic Shape Cues, Invariants, Priors, and Interface Design. in *Human Haptic Perception - Basics and Applications*, M. Grunwald (ed.), Birkhauser Verlag. pp. 381-392. [5]

Hayward, V. 2007. Physically-Based Haptic Synthesis, In *Haptic Rendering: Foundations, Algorithms and Applications*, T. M. A. Otaduy and M. Lin (Eds), Wellesley, MA: A. K. Peters, Ltd., 297-309. [4]

Rovan, J. and Hayward, V. 2000. Typology of Tactile Sounds and Their Synthesis in Gesture Driven Computer Music Performance. In *Trends in Gestural Control of Music*. Wanderley, M., Battier, M., (Eds). Editions IRCAM: Paris. pp. 297-320. [42]

Hayward, V. and Armstrong, B. A. 2000. A New Computational Model of Friction Applied to Haptic Rendering. In *Experimental Robotics VI*, Peter Corke and James Trevelyan (Eds), Lecture Notes in Control and Information Sciences, Vol. 250, Springer-Verlag, pp. 403-412. [95]

Hayward, V. 1996. Performance Measures for Haptic Interfaces. In *Robotics Research: The 7th International Symposium*, Giralt, G., Hirzinger, G., (Eds.), Springer Verlag. pp. 195-207. [85]

3. Granted Patents (plus five pending)

US 7,369,115 06/05/08. Haptic devices having multiple operational modes including at least one resonant mode. M. Cruz-Hernandez, D. Grant and V.Hayward.

US 7,336,266 26/02/08. Haptic pads for use with user-interface devices. V. Hayward, R. Alarcon and L. B. Rosenberg.

US 7,077,015 18/07/06. Method and Apparatus To Reproduce Tactile Sensations. V. Hayward, J. Pasquero, V. Levesque.

EPO WO2004109488 16/12/04, System And Method For Low Power Haptic Feedback, V. Hayward.

US 6,693,516 17/02/04. Electro-Mechanical Transducer Suitable For Tactile Display and Article Conveyance. V. Hayward.

US 6,781,569 24/08/04. Hand Controller. P. Gregorio, V. Hayward, C. Ramstein.

US 6,445,284 03/09/02. Electro-mechanical transducer suitable for tactile display and article conveyance. M. Cruz-Hernandez, V. Hayward.

US 6,020,967 01/02/00. Differential Optical Displacement Sensor. P. Gregorio, D. Grant, V. Hayward.

US 6,116,844 12/09/00. Mechanism for placing and orienting articles, V. Hayward.

4. Invited Presentations

2000 Distinguished Lecture Series, Dept. of Computing Science, University of Alberta.
2001 Opening Lecture, IEEE ICMA Conference, Osaka, Japon.
2001 Plenary Presentation, Workshop on Interact. multimodal Telepresence Syst., Munich, Germany.
2004 Keynote Speaker, Eurohaptics, Munich, Allemagne.
2005 Keynote Lecture, Dutch-Belgium Haptics Society, Bruxels, Belgique.
2006 Opening Lecture, 2nd Enactive Workshop, Montral.
2006 Keynote Speaker, 8th International IFAC Symposium on Robot Control, SYROCO 2006.
2006 Invited Lecture, Journes ROBEA, CNRS, Paris, France.
2007 Lecturer, The Cutting Edge: Royal Society Lectures in Science, McGill University
2009 Lectio Magistralis, University of Verona.

5. Research Expeditions

Not applicable.

6. Organization of International Conferences

Since 1999, the applicant been on the program committee of 23 international conferences. Of particular note is my co-organizing with Prof. J. M. Hollerbach (Univ. of Utah) the IEEE-RAS/IFRR 2006 School of Robotics Science on Haptic Interaction. This was the third summer school offered through co-sponsorship by the IEEE Robotics and Automation Society (RAS) and the International Foundation of Robotics Research (IFRR). The school hosted 35 Ph.D/Post-doctoral students from across the world, specifically from Belgium, Canada, Italy, Japan, France, Germany, Greece, Mexico, the Netherlands, Spain, Switzerland, Turkey, the UK, and the USA who were instructed by ten internationally reknown professors from Europe, the USA, and Japan.

7. Awards and Distinctions

2002 The E. (Ben) & Mary Hochhausen Award for Research in Adaptive Technology For Blind and Visually Impaired Persons.
2003 Outstanding Reviewer for Automatica, J. of the International Federation of Automatic Control.
2006 Best Demonstration Award, Eurohaptics 2006, Paris.
2006 Best Paper Award, ACM CHI'06 Conference, Montral.
2006 Best Paper Award, 14th Symposium on Haptic Interfaces For Virtual Environment And Teleoperator Systems, IEEE VR 2006.
2007 Best Paper Award (applications), World Haptics 2007.
2008 Fellow of the IEEE.

8. Memberships of Editorial Boards

08- Associate Editor, IEEE *Transactions on Haptics*.
07- Associate Editor, ACM *Transactions on Applied Perception*.
98- Member of Governing Board, *Haptics-e*.

The main focus of Wexler's work as a psychophysicist has been on the interaction between perception and the perceiver's own movement. Traditionally, perception has been studied in the purely passive observer: unmoving, and unable to act on his or her environment—action that in turn modifies subsequent perception. The divorce of perception from action has been due to theoretical influences—a purely information-processing approach to perception and cognition—but also the methodological difficulties of closing the loop between action and perception. Some of Wexler's most important accomplishments have been ways to incorporate action into the study of perception, without any loss of rigour that accompanies the normal study of perception. The problem of interaction between perception and the perceiver's action can be addressed from both directions: the effect of perception on action, and the more difficult problem of the effect of action on perception. He has made important contributions to the study of both types of problems.

Several important discoveries of previously unexpected relationships between action and perceptual constancies—the extraction of invariant features such as absolute size, three-dimensional shape, or position in space—from sensory information 'contaminated' by accidental features such as absolute distance, viewing angle, or eye position. For example, an important way of extracting 3D shape from optic flow relies on the tacit assumption of rigidity, in the so-called structure-from-motion (SFM) process. However, rigid motion can be produced in two different ways: when rigid objects move independently of the observer, or when the observer moves through a stationary environment. Prior to our work on this subject, it was thought that the only thing that mattered to SFM was relative motion, or, in other words, that SFM was based on the retinal, optic-flow stimulus alone. Using a careful technique in which we equated optic flow in moving and immobile observers, we showed that this is not true: moving and immobile observers can perceive the same optic flow as different 3D shapes (Wexler, Panerai, Lamouret & Droulez, 2001; van Boxtel, Wexler & Droulez, 2005). Moreover, the same optic flow in actively and passively moving observers can lead do different perceptions of 3D shape (Wexler, 2003). These discoveries have led to a new theoretical understanding of optic flow processing, in which the venerable rigidity assumption is supplemented by a new assumption, object stationarity in an observer-independent reference frame. The stationarity assumption has been subsequently verified in his work (Wexler, Lamouret & Droulez, 2001), as well as from other laboratories (e.g., Naji & Freeman, 2004). These ideas have proven quite fertile in current work, in which we have shown that, contrary to all expectations in a very old subject, that size constancy is more robust during observer motion than object motion. Finally, the stationarity assumption has been integrated with the rigidity assumption in a unified bayesian model of optic flow processing (Colas, Droulez, Wexler & Bessière, 2007), which accounts for a great deal of empirical data, and which is expected to have application to artificial vision and robotics.

A different way in which motor and perceptual processes interact is in the process of *prediction*. Motor planning leads not only to motor commands descending to the peripheral muscles, but also to the so-called efferent copy for the central nervous system's own use in anticipating the outcome of the planned movement, in order to, for example, prepare perceptive systems for the upcoming changes in order to distinguish them from observer-independent events. Although physiological studies had long shown evidence for such processes in animals, they were able to document their existence in man using an elegant, non-invasive psychophysical paradigm (Wexler & Klam, 2001), in which they showed that predicted trajectories of observer-manipulated objects advance further than those of passively observed objects. The existence of such sensorimotor anticipation offers an interesting solution to a very important problem in psychology, namely how to explain our ability to manipulate mental images of objects. Mental image transformations, such as mental rotation, have received great attention in cognitive psychology starting from the early 1970's, and were thought to be examples of specialized, modular processes. However, the existence of sensorimotor anticipation offers an alternative model: if we can plan an action and inhibit its execution at the last minute, sensorimotor anticipation could nevertheless drive the representation of the to-be-acted-upon object into the configuration it would have, had the action been executed. This sensorimotor model of mental image transformations has the advantage of parsimony, as it explains psychological processes using well-documented physiological ones, rather than invoking ill-defined and ungrounded modules. They were able to confirm this model using a dual-task paradigm, in which we showed, against all expectations, that unseen *manual* rotations

interfered with concurrent *mental* rotations: mental rotation performance was improved when it was in the same direction as the manual rotation, and impaired when it was in the opposite direction (Wexler, Kosslyn & Berthoz, 1998). This work has had a tremendous impact in cognitive psychology and neuroscience. It has led to a large number of fMRI and TMS studies that have searched for and found a role for the motor and premotor cortex in cognitive processes such as mental rotation. Other studies have documented that this motor-cognitive interference is even stronger in children than in adults, providing further for a sensorimotor origin of these mental transformations. Routinely cited in standard textbooks of cognitive psychology, it is fair to say that our result has revolutionized the understanding of mental image transformations. In Wexler's lab, we are currently studying whether the sensorimotor model can be extended to large-scale spatial reasoning.

Another domain where Wexler has made recent contributions to is the study of eye movements and visual perception. A particular interest has been the study of the interaction with three-dimensional vision, subject that had been neglected, probably because in humans eye movements create almost no parallax, and therefore result in very little 3D information. However, since vision is fundamentally an active, rapid sequence of information-seeking saccades, and because vision is vitally concerned with the 3D characteristics of the world, Wexler has recently been able to uncover two very interesting ways in which 3D vision and eye movements interact. The first is an effect of saccadic eye movements on vision. Ever since the 19th century, physiologists and psychologists have been studied *spatial constancy*—how the world appears stable in spite of frequent and rapid eye movements that cause retinal images to constantly shift. On the other hand, a related but separate question had completely escaped all attention: since the eye is itself a 3D object, when it rotates in the head, all external surfaces undergo an equal-and-opposite rotation, in depth, with respect to the eye. However, we seldom perceive these relative rotations. After showing that this *3D spatial constancy* cannot be reduced to the more familiar form of spatial constancy, he uncovered a phenomenon that gives an important clue about how 3D spatial constancy might be achieved: a strong but short-lived bias in the perception of ambiguous 3D motion while the brain prepares a saccade (Wexler, 2005). This result indicates that ocular effence copy results in an active preparation for the potentially disruptive 3D consequences of every eye movement.

Approaching the problem from the other end, Wexler has also shown an interesting effect of 3D vision on spontaneous, exploratory eye movements (Wexler & Ouarti, 2008). An important problem in active vision is to predict where people look when they scan visual scenes. This problem is of interest both in order to characterize the inputs of vision, and in the creation of artificial active vision systems. The problem had always been approached from the standpoint of the 2D projection of scenes. Some correlations between 2D properties and spontaneous eye movements have been found, but they predict little of the natural variance of spontaneous eye movements. We asked the following question, for the first time it seems: do specifically 3D aspects of a visual scene have any effect on where people look? Using planes inclined in depth, we found an overwhelmingly positive answer, and a very simple rule that predicts eye movements: they tend to follow surface depth gradients (Wexler & Ouarti, 2008). This results has been found to generalize to all depth cues tested, and to complex objects composed of more than one surface. Besides providing an original answer to the old problem of where people look when they look at natural scenes, our result opens up a number of interesting avenues of research. One is the use of spontaneous saccadic eye movements—which are the only voluntary movements that are almost mature at birth in humans—as a probe to study 3D vision in human infants.

1. Education

1988 BA (Physics), Columbia University, USA.
1994 PhD (Theoretical physics), Princeton University (USA). Thesis title: Random surfaces on large graphs.

2. Positions

88-89 Research assistant, Department of Physics, Princeton University.
89-93 Teaching assistant, Department of Physics, Princeton University.
94-94 Postdoctoral fellow, Niels Bohr Institute, University of Copenhagen.
94-95 NATO/National Science Foundation postdoctoral fellow, Laboratoire de physique théorique et hautes énergies, Université de Paris VI.
95-96 Postdoctoral Fellow in experimental psychology, Fondation Fyssen, Paris.
97-01 Postdoctoral researcher, Laboratoire de Physiologie de la Perception et de l'Action, Collège de France, Paris.
01-06 Research scientist, CNRS. Appointed to Laboratoire de Physiologie de la Perception et de l'Action, Collège de France, Paris.
07- Research scientist (chargé de recherche), CNRS. Appointed to Laboratoire Psychologie de la Perception, Université Paris Descartes.

3. Teaching

Direction or co-direction of 3 PhD students (Camille Morvan, Irene Fasiello, Emmanuelle Combe) and numerous masters projects.

Yearly teaching of two courses (P3: Movement; AE: Experimental workshop) in the Master des Sciences cognitives (EHESS/ENS/Université Paris Descartes).

10-Year-Track-Record

1. Top 10 publications (out of 21, [citation count] from ISI)

Wexler, M. and Ouarti, N. 2008. Depth affects where we look. *Current Biology*, 18:1868–1872. [0]

Wexler, M. and van Boxtel, J.J.A. 2005. Depth perception by the active observer. *Trends in Cognitive Sciences* 9:431–438. [11]

Wexler, M. 2005. Anticipating the three-dimensional consequences of eye movements. *Proceedings of the National Academy of Sciences of the* USA, 102, 1246-1251. [6]

Morvan, C. and Wexler, M. 2005. Reference frames in early motion detection. *Journal of Vision*, 5(2):131-138. [8]

van Boxtel, J.J.A., Wexler, M. and Droulez, J. 2003. Perception of plane orientation from self-generated and passively observed optic flow. *Journal of Vision*, 3(5):318–332. [6]

Wexler, M. 2003. Voluntary head movement and allocentric perception of space. *Psychological Science*, 14:340–346. [15]

Wexler, M., Lamouret, I. and Droulez, J. 2001. Stationarity: An allocentric criterion in visual perception. *Vision Research*, 41:3023–3037. [16]

Wexler, M. and Klam, F. 2001. Movement prediction and movement production. *Journal of Experimental Psychology: Human Perception and Performance*, 27:48–64. [12]

Wexler, M., Panerai, F., Lamouret, I. and Droulez, J. 2001. Self-motion and the perception of stationary objects. *Nature*, 409:85–88. [36]

Wexler, M., Kosslyn, S.M. and Berthoz, A. 1998. Motor processes in mental rotation. *Cognition*, 68:77–94. [120]

2. Five Monographs and Chapters in Books (out of 9, [citation count] from GoogleScholar)

Wexler, M. 1999. Inductive learning with external representations. In *Understanding representation,* A. Riegler and M. Peschl, eds. Plenum Press, New York. [4].

3. Granted Patents

None.

4. Invited Presentations

None.

5. Research Expeditions

Not applicable.

6. Organization of International Conferences

Prediction-Action-Perception. International workshop, co-organized with Julie Grèzes. Paris, 18-20 May 2005.

7. Awards and Distinctions

None.

8. Memberships of Editorial Boards

None.

ii. The Research Project

Proposal Summary: During mechanical interaction with our environment, we derive a perceptual experience which may be compared to the experience that results from acoustic and optic stimulation. Progress has been made towards the discovery of mechanisms subserving the conscious experience of interacting with mechanical objects. This progress is due in part to the availability of new instruments that can tightly control mechanical stimulation of both the ascending, i.e. sensory, and descending, i.e. motor, pathways. The research program describes the design of new mechanical stimulation delivery equipment capable of fine segregation of haptic cues at different length scales and different time scales so that controlled stimuli may be delivered with the ease and accuracy which is today possible when studying vision or audition. The purpose of this equipment is to disentangle and recombine the individual cues used by the brain to recover the attributes of an object, leading to the identification of the computations that must be performed to achieve a perceptual outcome. In vision and audition, much is known of the nature of the peripheral and central computations, but in touch, for lack of proper equipment, little is known. From this knowledge, I aim at developing a theory of haptic perception which rests on the observation that these computations are distributed in the physics of mechanical contact, in the biomechanics of the hand, including the skin, the musculoskeletal organization, innervation, and in central neural processes. This research program is rich in applications ranging from improved diagnosis of pathologies, to rehabilitation devices, to haptic interfaces now part of consumer products and virtual reality systems.

Specific Aims

The research program, for the next five years, is inspired by David Marr's notion that the computations performed by the central nervous systems in perceptual tasks must be organized by levels of abstraction and that these computations must solve specific problems independently from their implementation [1]. It is therefore needed to develop techniques able to delineate those levels of abstractions in haptic perception. I propose to articulate a research program according to the scheme outline in Table A. Each part of the program addresses a specific time scale and a specific length scale, and has distinct hypotheses; it proposes apparatuses able of delivering appropriate stimuli and to control and measure motoric behavior; it has a set of psychophysics experiments to test hypotheses and/or obtain basic human performance data (when not available); and it has a mathematical formulation of the problem to be solved, yielding possible computational approaches to solve it.

Table A: Program Organization

Time scales:	skin deformation: 1-100 ms	contact transients: 10-100 ms	movements: seconds
Length scales:	skin ridge $\approx 300\ \mu$m	finger contact surface ≈ 1 cm	limbs reach 0.1–1 m
Dominant physics:	tribology dynamic propagation	continuum-mechanics	kinematic & dynamics
Mathematics:	inverse & direct problems	filtering and interpolation	differential geometry & homotopy
Stimuli:	traction distributions	force fields	global contact features

The above table summarizes the components that will enter into the theory. They rely a small number of cues, or distinct sources of information—the elements of touch—arising from:

1. slip,
2. intra-contact deformation patterns,
3. contact velocity,
4. local deformation,
5. motoric activity, and
6. global deformation.

These elements correspond to cutaneous stimulation, proprioceptive information, and motor commands, and these "early touch" signals are sufficient to compute objects attributes including shape, weight, size, surface micro-geometry, and material properties.

A key methodological tool will be the specification of a *'plenhaptic function'* (by analogy to the 'plenoptic function' in vision) or abstract function that completely specifies all possible interactions with an object. It is anticipated that this function operates in a high-dimensional space (> 8) and hence has essentially the same complexity as the plenoptic function, which demonstrates the formidable computational task the brain faces when perceiving an object mechanically *through contact surfaces*. Haptic perception is indeed comparable to vision in its tremendous information compression capability.

Higher level aspects of haptic perception that will not be addressed include those related to attention, learning and memory, development, and aging. It is however clear that our results will have major contributions to make to the study of those topics.

In the longer term, I intend to relate the expected findings of this program to studies involving measurements on living organisms, including studies involving neural correlates via imaging, evoked potentials, stimulation, and neurography. In the shorter term, however, I propose that the presently described program, based on systematic behavioral studies carried out with the help of novel and carefully engineered equipment, will deliver the models at the levels of abstraction that are appropriate for rigorous testing using appropriate techniques, even at the risk of excessive reductionism.

Background and Significance

Since the early works of Géza Révesz (1878–1955), David Katz (1884–1953), and modern and contemporary psychologists, most notably James Gibson, and today, Susan Lederman, the haptic channel is usually understood to result from the combination of motor and sensory activities, particularly but not exclusively in the hand, resulting in the conscious experience of the presence and the qualities of objects and surfaces. These and other works have provided a wealth of information regarding the behavior the humans engaged in haptic activities, including perceptual thresholds, behavioral patterns, and levels of performance in various detection and discrimination tasks. However there hardly has been any work on the computational significance of these results, which provides us today with a tremendous research opportunity.

A few have suggested the notion that haptic perception relies on specific computational processes in the fields of both life sciences and engineering. Klatzky and Lederman (1993) must be credited to have first considered this possibility [2]. However, their model, based on constraint satisfaction, is at a much higher level than those I propose to develop and possess more descriptive power than predictive power. Solomon and Turvey have shown that humans can utilize natural invariants to haptically estimate the length of a rod and thereby solving a simplified, linear type of inverse problem where the causes are computed from the effects [3]. Perhaps the greatest successes at considering haptic perception computationally using models that have predictive power were obtained by Marc Ernst (sensory integration [4, 5]) and Daniel Goldreich (spatiotemporal illusions [6]) who both view perceptual outcomes as the result of the solution of maximum likelihood problems. These aforementioned results provide great motivation for developing what we might call a theory of "early haptics" that could described precisely and quantitatively the sources of information that the brain can use to experience objects and to behave in order to experience and manipulate them.

It has been the observation of engineers that tactile sensing depended on a computational operation. Fearing and Hollerbach investigated the subcutaneous deformations induced by flat surfaces, edges and corners to draw conclusions regarding the requirements for receptors situated beneath the surface. Their conclusions were about the requirements for the distribution of such receptors to achieve a given level of discriminative performance [7]. Another background work of great relevance is that of Ferrier and Brockett who wondered whether the shape of a membrane could be reconstructed from two-dimensional data and used elastic energy minimization theory to invert this problem stably [8]. Bicchi et al. showed that organized spatiotemporal patterns of skin deformation could be viewed as "flow" and hence be operated on to detect movement [9]. Kikuuwe et al. performed detailed analysis, in closed-form, of the strain propagation patterns inside a continuum to show that periodic

traction surfaces could be use to amplify the effects of a Dirichlet boundary condition at a distance inside the surface [10], from which is can be inferred that the mechanics of the skin could be used to perform computations. Wang and Hayward used these results to show that radically different types of time-varying boundary conditions could give rise to the same signals beneath the skin [11].

Artificial skin has been investigated from the very beginnings of robotics research [12], and even today, most researches focus on its manufacturing [13], with occasional works on the computational questions raised by its availability [14]. However, the computational tasks considered in robotics are often likened to 2D image processing [15], which, in my view, is too great a simplification of touch as it is observed in living organisms, although recent works have started to tackle the question of sensorimotor coordination in a robotic hand [16]. From this viewpoint, the results of the proposed research will have contributions to make to robotics and, by extension, to advanced extremities prosthetics engineering [17]. Physiologists and biomechanics experts have considered the role played by mechanics in touch but this role was not associated with any other function that a sensory function [18, 19, 20, 21, 22].

Why is the background on computational aspects of haptic perception sparse? Perhaps it is because it requires the investigation of difficult mathematics, non-intuitive physics, and above all, apparatuses that are not available commercially. This proposal is designed to address this challenge and to develop a theory that has predictive power, and hence, is close to applications. It is expected to have impact in all the fields mentioned and its development to give devices of high practical importance.

General predictions

1. Multi-source perception of object attributes. A first general expected outcome of the research is a clear demonstration that the haptic channel operates from a variety of sources of information, and thus, that there does not exists a simple correspondence between sensory organs and the consciously perceived attributes of objects. A good example is that of the curvature of objects since the mechanisms needed to recover it vary fundamentally according to the length scale. In fact even when the scale is small, say, to experience the roundness of a pen, we expect to show that there is no need for "curvature sensors" but that curvature is recovered by the brain from a great variety of different mechanical effects [23]. Such prediction can be made for texture, weight, size, and compliance. We hope for all these cases to be able to give a precise account of the computation that must be performed to recover them.

2. Role of efference in haptic perception. A second general prediction is the fundamental contribution of efferent information from central action planning and execution to haptic perception, that is Sperry's 'corollary discharge' and von Holst and Mittelstead's 'efference copy'. To the knowledge of the applicant this idea has never been put forward explicitly, and yet there is evidence that the efference copy plays at least two crucial roles in haptic perception. The first is the classical attribution of its role which is, like in vision, to enable an organism to distinguish the variations of the afferent signals due to the motion of its own body from those of external objects. But there is a second that regards directly the motoric component of haptic perception. When one interacts with an object one works against a force field acting on the limbs, which in the simplest case is that due to gravity. The same motor command against different objects can give rise to different movements that yield combinations of, possibly zero, rigid-body displacement but always of finite local deformation in the connective tissues, tendons, and muscles. It is a general hypothesis that it is the "difference" (in an extended sense, since the everyday notion of difference does not apply here) that informs the brain of coarse object attributes such as weight, shape, compliance, and mobility. We expect to be able to cast the attendant computations in the mathematical forms of inverse problems where the efference copy participates in the givens to the problem as much as the afferent signals do.

3. The computational skin. A third general prediction is that the biomechanics attributes of the skin in particular perform a form computational tasks which increase the sensory capabilities of the hand much beyond what can be expected from considerations of innervation density. In other words it is proposed that the skin mechanics are such that the nervous can operate at resolutions that are beyond those predicted by simple sampling considerations. It is proposed that the papillary geometry

of the dermal layers combined with the beautiful three-dimensional distribution of the receptors in this geometry plays a role that could be loosely compared to the role of early processing in the retina or in the cochlea. Namely, the "mechanical computations" done by the skin would have the effect to give tactile sensing robustness against noise and the capability of detecting relevant *features* at a very fine—sub-Nyquist—scale, and not simply a "faithful image" of what is being touched. This hypothesis is quite distinct from the purely sensory enhancement role ordinarily attributed to the skin mechanics.

4. The role of slip. A fourth general prediction concerns the role of slip. Since haptic sensations result from mechanical events, it is natural to consider them systematically. When two bodies come in contact, they deform locally. According to the load applied, different sequence of events can be set in motion. They can remain stuck or can transition into relative slip. The notion here is that the dynamics of the transition hold important haptic cues regarding the nature of the touched object most notably the material it's made of. Inferring the material's properties from the dynamics of transition happens to correspond to the inverse solution of a boundary-free problem, a problem where the location of the boundary isn't known (what determines the shape of an ink blot). The corresponding hypothesis is that the brain solves this inverse problem for perceptual purposes much beyond simply detecting the incipient slip of an object. The second role is that when slip is established the brain if possible estimates the slip velocity and uses the estimate to compute shape. In this, the hypothesis here is that the skin actually plays a proprioceptive role in that it informs the brain of the relative velocity between a skin contact and an object and that this role is in essence computational.

5. Internalization of hand properties. When a hand interacts with an object sensory information arises both from cutaneous and proprioceptive information. In fact these two sources are not independent: they are related by both the viscoelastic of the hand it and from its shape. In other words a given object touched with different hands will give different sensory information. It is therefore necessary for the brain to have internalized the hand's properties to make any use of the sensory information. For instance when touching a flat surface with the finger tip, the contact surface is by-and-large circular but when touching the same surface with the thenar eminence (the bulge at the root of the thumb) the contact surface isn't. Other observations such as these can be made involving differential quantities. The fifth hypothesis is that the brain internalizes the geometric and viscolelastic attributes of the hand to perceive objects haptically and that the corresponding computations can be described in a precise mathematical language.

6. Conservation principles. Lastly, it has been often observed that the information processing capacity of the brain is great, but finite, and that this fact may be used to explain information processing strategies in vision and audition. In haptics the application of this observation have been so-far limited to the study and discovery of the principles of the organization of movement (motor invariants, isosynchronicity, Fitts' law). It is proposed that haptic perception is also subject to similar principles. For instance, it is hard to explain the discriminative power of touch simply from the signals delivered by tactile receptors; See [24] for a review of the roles of the fast and slow adaptive mechanoreceptors. The sixth hypothesis holds that the haptic information processing rate is constant and therefore the brain trades optimally spatial and temporal acuity to reconstruct the perception of objects as it's been shown in vision [25].

These predictions are all testable using the methods and apparatuses described in the section "Scientific Proposal" and each are related to one or several entries of Table A.

Expected outcomes and impact

One outcome of this program will be to provide principled explanations to the numerous tactile illusions that are known today, see [23], as well as for those being discovery at an increasingly high rate ([26, 27] among others), and hence gaining new insights into perceptual processes. The understanding of haptic perception lags far behind that of other sensing modalities. The characterization of the conditions under which illusions arise has always been a powerful engine of progress in the cognitive neuroscience of perception. Illusions are becoming increasingly important as the techniques for the study of neural correlates become available and increasingly accurate (cf. cortical optical imaging, fMRI, and others).

The systematic knowledge gained from this research program will benefit the systematic design of existing haptic transducers, but perhaps more importantly, will provide new methods to realize simpler and more effective displays, compared to those that are available today. As stated at the outset, the theory to be developed is predictive, hence, quantitative. Design engineers need more information than qualitative data, they need numbers which the development of the proposed theory is designed to provide. Today the applications of haptic interfaces are mostly confined to high-end applications (manufacturing design bureaus in automotive and aerospace industries, medical equipment in clinical and training settings) or low-cost, low-capabilities (rumble effects in the Wii™ and other gamepads, vibrotactile effects in portable phones, automobile controls). Many sensory-supplementation applications for special need populations, the blind and visually impaired, the deaf and auditory impaired, are either too costly or perform below the needed performance levels.

The knowledge of the operating principles of haptic perception and availability of equipment designed to optimally stimulate it has applications in health issues. Many conditions are associated with sensory and motor deficits, not only following stroke or Parkinson disease but peripheral neuropathies, from diabetes, HIV-related and other factors such as pressure ulcers of bedridden patients. In all these cases, testing methods are, to say the least, rather primitive compared to what is available for vision and audition. Given the successes of force feedback devices in the rehabilitation of stroke patients, if the past is any indication for the future, more general haptic interfaces able to address the more general types of interactions described is this proposal are promised a bright future.

Scientific Proposal

As discussed earlier, the general approach is to consider a 'plenhaptic' function that adopts the following form:

$$H_h(p, d, v, t), \tag{1}$$

where $H_h \subset \mathbb{R}^6$ is the displacement of all the points of the surface of an object (or of a complete haptic scene say, all the objects in my pocket or on my desk at this moment) considering all possible interactions of this object with my hand, symbolized by the index h (or with any tool in general). There, $p \in \mathbb{R}^2$ is the initial point of contact, $d \in \mathbb{R}^3$ is the subsequent deflection from this contact, $v \in \mathbb{R}^3$ is the subsequent velocity of this contact, and $t \in \mathbb{R}^+$ is time to express the fact that the object or scene can vary with time. For example if we consider that both the object and the probe are ideally rigid and that the object is immobile, then this function reduces to $H(p) \subset \mathbb{R}^3$ which is nothing but the shape of the object or the set of all the points of its surface. In this idealized case, and assuming perfect sensory knowledge, then the task of the brain would be to recover the *shape* H from a 'pencil' of *curves* in $\mathbb{R}^3$ (they only share the property of lying on the same surface) which vividly illustrates the computational nature of haptic perception. In the opposite extreme, which is that of a liquid, the object is displaced such that $H = h$; in other words, the object has no shape, or rather it has a shape which is a "copy" of that of the hand. In real life, almost all cases in-between may be considered.

Next, we consider that the human haptic channel has, in essence, access to low dimensional projections of this function on subspaces that are determined by its motoric and sensory capabilities. These projections are in turn sampled in time and space, notably through small contact surfaces, giving the brain the task to recover the desired object attributes that are needed to accomplish a desired task manipulation or a perceptual task. In Table 1, page 11, we have proposed to reduce this very complex problem into a manageable set of computational tasks operating at different length and time scales. Given the complexity of the complete problem, it is not surprising that the brain cannot solve all cases, giving rise to the aforementioned haptic illusions.

State-of-the-art and objectives

To the knowledge of the applicant, the research approach developed thus far is original and hence the literature is sparse. In the section "Background and Significance", we have seen that the greatest source of insights comes from engineers and roboticists such as P. Dario, P. De Rossi, N. J. Ferrier and R. W. Brockett, R. Fearing and J. M. Hollerbach, A. Bicchi, R. Kikuuwe for their consideration

of contact mechanics and others such as R. D. Howe, M. Cutkoski and J. K. Salisbury with their work on robotic hand control. Physiologists and psychologists such S. J. Lederman, R . Klatzky, S. Millar, A. A. Wing, A. M. Smith, K. O. Johnson, R. S. Johansson, M. Srinivasan, A. W. Goodwin, M. O. Ernst, F. Norman, M. A. Heller, J. F. Soechting, M. Hollins, and others, have described a great variety of haptic behaviors in relation to the neurophysiology of haptic perception, but, as commented, rarely a discussion related to the computational nature of haptic perception seem to have been ever engaged. Perhaps, the work of A. M. L. Kappers and her collaborators of the University of Utrecht on the perception of the curvature of objects and the structure of the haptic space, is the most closely related to our subject. In fact, it is the research of J. J. Koenderink and his collaborators (spanning more than three decades) that bears the closest resemblance with the research program described here, but the link is not immediate since the physics of vision are so different from the physics of touch.

The **objectives** correspond to the six hypotheses outlined in the Extended Synopsis, namely:

1. The same object attributes, specifically shape, texture, and compliance can be obtained from different sources of information;
2. Efference (descending commands) are essential in enabling the distinction between self and external motion, that is mobility, but also in experiencing shape and compliance;
3. The skin biomechanically detects features and is not just an "imager";
4. Slip informs of material properties dynamically and participates in shape revovery;
5. Hand properties, geometry and mechanics, are internalized;
6. Information rate is conserved.

Methodology: Apparatuses

With reference to the Table 1 page 11 of this proposal, this section discusses the approaches proposed to deliver the stimuli that are appropriate to our scientific objectives.

Apparatus T. Traction distributions: Small length scale, small time scale.

State of the art. The applicant's previous research has developped a technique to create small-scale skin deformations at high temporal resolution. Starting from an initial device deployed in 2000 [28], the first *laterotactile* display consisted in an array of 64 piezoelectric actuators bonded to a membrane covered with 112 cylindrical skin contactors (Figure 1a). The extension and contraction of the actuators resulted in a deformation of the membrane and in the lateral displacement of the tips of the long skin contactors. Later, a new type of laterotactile display consisted in a 10 by 10 array of skin contactors produced by stacking piezoelectric "combs" cut out of single bimorph plates. The elimination of the membrane in favor of direct contact with the actuators greatly simplified the manufacturing but the weakness of the sensations remained a problem. A second generation laterotactile display, the stress, resolved some of the remaining issues (Figure 1b, [29]) through a better understanding of the mechanical behavior of the fingerpad skin [30]. The latest stress prototype has of a matrix of 8 by 8 actuators forming an active area of approximately one cm^2 with 64 tactile elements (Figure 1c). The tip of each actuator can be deflected by approximately 0.1 mm, and can produce a blocked force in the order of 0.15 N at 500 Hz. The display occupies only 150 cm^3 and weighs only 60 g.

Proposed work. The tactile transducer described above is very capable since it has the capacity to convey high-resolution tactile graphics to visually impaired users [31] (featured in the NewScientist, this device was also used in studies [32, 26]). We intend to initially carry out the proposed work with this readily-available system however its characteristics makes it ultimately unsuitable for the present program. This type of display operates by creating traction at the surface of the skin at small scale taking advantage of St-Venant's principle. Lateral traction creates highly focused deformation inside the skin at a distance which is roughly half the distance between two 'tractors', targeting the skin mechanoreceptors located 0.5-0.7 mm beneath the skin. The doubly-cantileved design that allows us to use well-proven piezoelectric actuators also come with limitations that go beyond having to drive the display with high voltages. We also need to measure displacement and force at the skin surface. In other words we also need to use the system as an actuator as well as a sensor. It is in principle possible to do this with piezoelectric actuators but there is a more direct route to achieve this purpose.

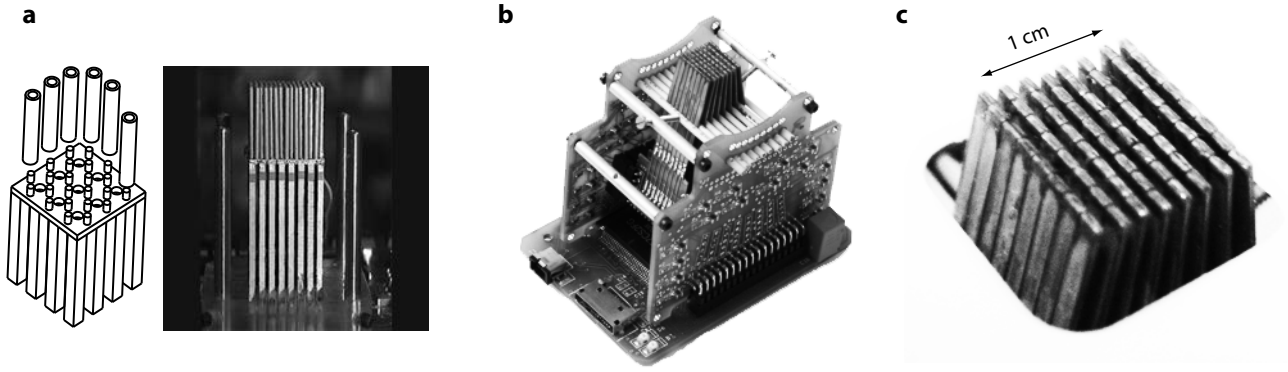


Figure 1: (a) First, (b) third generation of display prototypes. Active contact surface (c), 1 cm^2.

We propose a new generation of displays that use miniature electromagnetic actuators that rely on the principle of variable reluctance. The force generated by these actuators is not derived from Laplace's force, they rely on the change of magnetic energy in an air gap $W = B^2/(2\mu_0)gA$, hence, the pulling force is $F = \partial W/\partial g$, that is, $B^2A/(2\mu_0) = (F_m)2\mu_0A/(2g^2) = (iN)^2\mu_0A/(2g^2)$. As can be seen, this type of actuator benefits from miniaturization. All calculations done and accounting for saturation in the iron, a variable reluctance air gap can pull 10^8 N/m^2. Even if we could achieve a force density that is two orders of magnitude smaller, a 1 mm^2 air gap could still pull 1 N. Since distributed displays are by nature discrete, and that small patches of skin can be stimulated only in one direction at a time, the fundamental measure of performance for a tactile display is the traction per unit of length, that is, the lineic force — the *one-dimensional-gradient of traction*. From our experimental biomechanical data, this approach is well within the reach of feasibility.

Besides allowing for much more compact, *monolythic* designs, as well as low voltages, variable reluctance actuators have also the great benefit that they can operate as exquisitely sensitive position and velocity sensors by monitoring the electric impedance; and hence can be used to monitor the mechanical impedance of an object coming into contact, allowing, for the first time, complete control on the tactile stimulation. Figure 2 show one of the several possible geometries of such laterotactile distributed actuators.

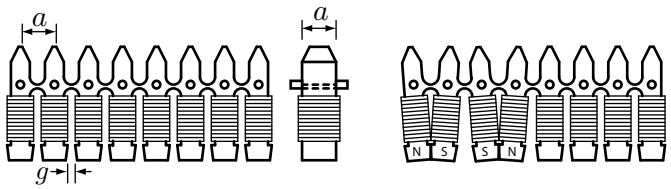


Figure 2: Variable reluctance distributed where $a \approx 1$ mm and $g \approx 0.1$ mm.

With the addition of normal force sensing, it will become possible to perform complete characterisation of the mechanical stimulation applied to the skin—at sub-millimetric length scale and sub-millisecond time scale—necessary to achieve our scientific ojectives. It is essential that this new device be made small enough to be combined with the two other devices described in the next two sections.

Apparatus F. Force and displacement fields at all scales.

State of the art. This type of stimulus is ordinarily provided by standard commercial force feedback devices such as the Sensable's Phantom™ or ForceDimension's Omega™ devices. Previous research has shown that while these devices are very capable, they are not intended to provide force fields with the accuracy required by the proposed research [33]. In a nutshell, their structural dynamics and their

inertial properties makes it infeasible to specify fast time-varying force fields. We prefer using a simpler device that can provide two-dimensional fields only but which has the advantages of being capable of providing accurate and well-characterized stimuli [34]. When combined with a force-intrumented stage this device is uniquely capable of creating *independent* force and displacement fields that can be explored [35]. Figure 3 shows the current design of the device which is presently used for several perceptual studies at the Université de Montréal [36]. This device has two stages. The first is an 'admittance' type device (specifies displacement, measures force) that operates from a stiff vertical displacement source (here implemented by a lead-screw drive, Figure 3a,b) coupled with a load cell that measures the normal scanning force of participants. This stage makes it possible to program 'displacement fields' that are orthogonal to the partipants' movements, Figure 3c. Concomitantly, the second stage is an 'impedance' type device (specifies displacement, measures force) makes it possible to program 'force fields' that are *orthogonal* to the displacement fields and hence do not interfere.

Proposed work. The applicant does not intend to employ this same apparatus in the proposed research but to develop a new one, based on similar principles, which is more capable, more flexible and above all, better suited to study the role of efference in haptic perception. A requirement for the new device to be developed is to no longer be limited to a single finger acting on a single nominally flat surface. We will design a new system that can provide force fields arbitrarily combined with displacement fields, not referenced to the mechanical ground, but between different fingers. The advantages of this new approach are multiple. First, the motor tasks will resemble better those that occur naturally since it is unusual to explore objects haptically with a single finger. Second, the muscle groups concerned are all located in the forearm and in the hand which provides better control and news opportunities to measure directly the motor output (the use of EMG recordings is not part of this proprosal but collaborative opportuties will be sought).

The design of a high-performance a device capable of specifying arbitrary force and displacement fields between two or three fingers is a considerable engineering challenge that can be achieved given the level of means that this grant, if accepted, would provide but which were never within reach of the applicant in the past.

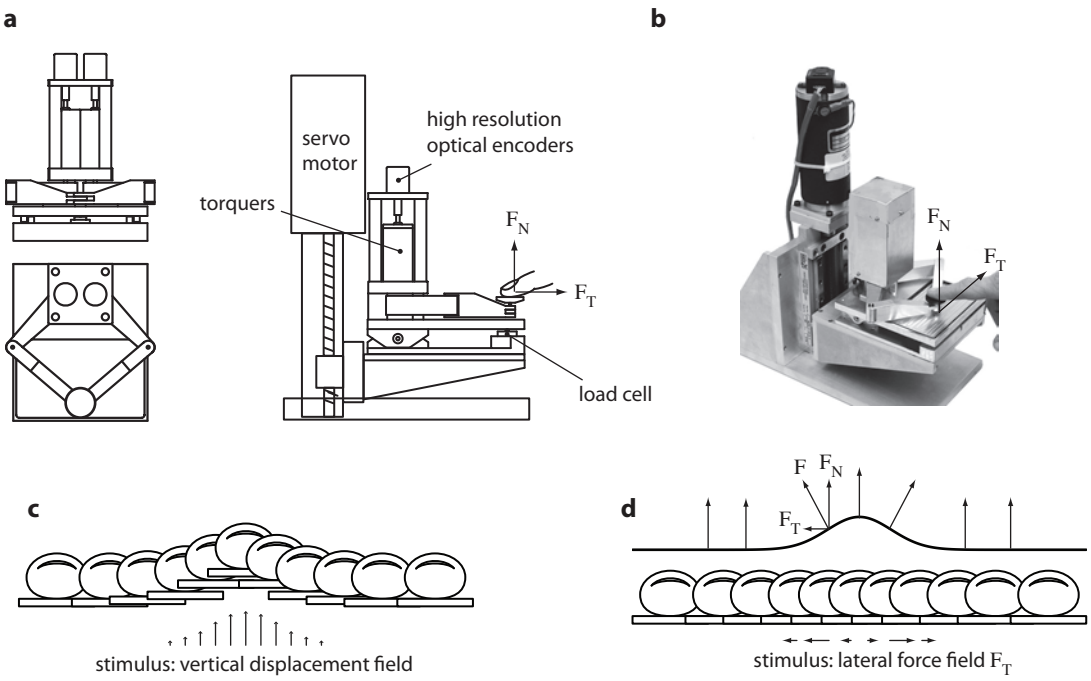


Figure 3: Existing apparatus to create decoupled force and displacement fields.

Apparatus G. Global contact features: large length scale, large time scale.

State of the art. In previous research the applicant and his collaborators have considered simplified versions of the problem of delivering the global features of a tactile contact via computer controlled hardware [37]. The apparatus used then was nothing but a flat plate servoed to rotated around a single point located *inside* the tip of finger. The resulting rolling motion makes it possible to mechanically decouple the point of interaction of a finger tip with the movements of the finger. Recently this technique was used to investigate the relative contributions of zeroth- and first-order geometric information to the perception of shape [38]. The apparatus used can be viewed in Figure 4a. By independently controlling elevation and orientation of a surface it is possible to specify independently the sources of information available to the perceiver. The apparatus, in its present state, allows one to simulate shapes as in Figure 4b with pure rolling in one dimension, that is without slip. A new technique (unpublished) allows us to also simulate cases involving combined contact rolling and slipping since, in general, manipulation involves the two forms of interation. In its simplest form, this technique involves asking the subject to scan a surface while detecting the position of the contact on this surface which is moved by computer to selectively deliver different types of information as illustrated in the rightmost two panels of Figure 4b. Position detection is accomplished by measuring, using muliple loadcells, the complete force vector applied to the contact (its magnitude, orientation and point of application). Preliminary results (unpublished) demonstrate the fundamental role played by slip when it can be disentangled from the other mechanics.

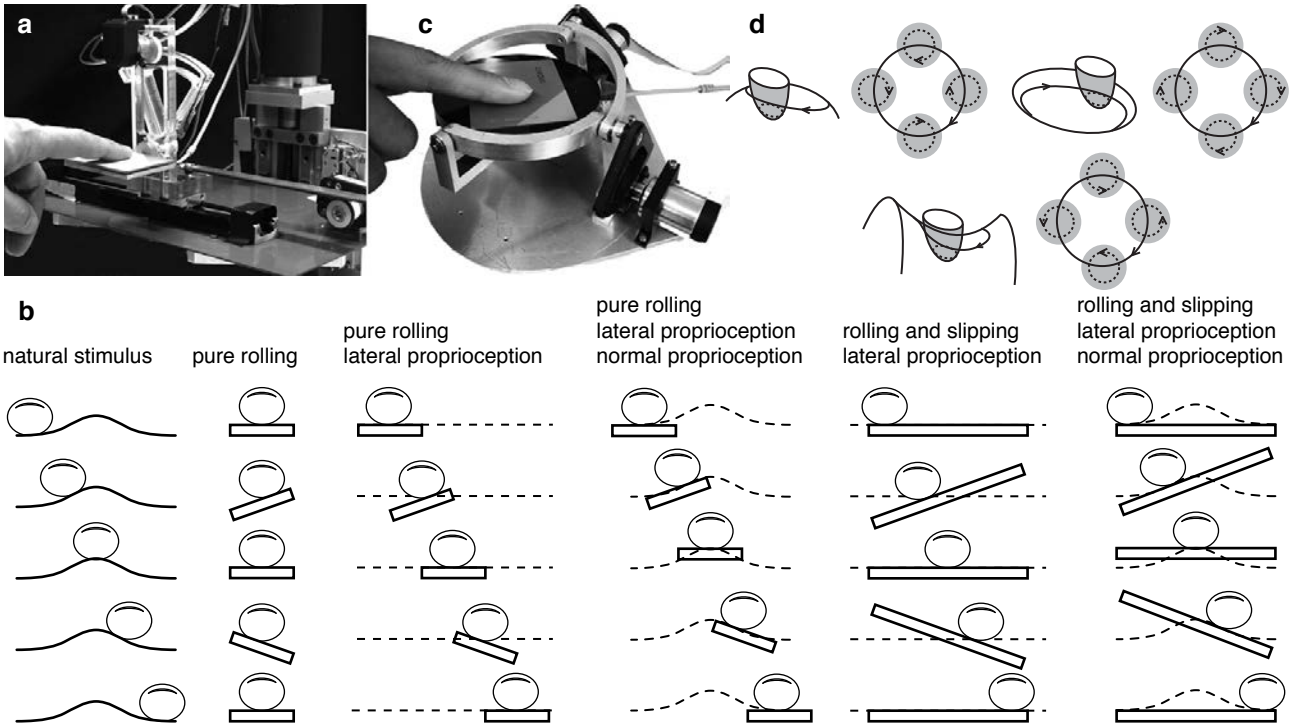


Figure 4: Existing and projected apparatuses to control the global contact features.

Proposed work. These techniques, although very successful, are insufficiently developed for the purposes of the proposed research. Specifically, what is described above has three limitations. The first is that the present hardware can only simulate profiles but shapes are embedded in space. An extension of the system seen in Figure 4a can be viewed in Figure 4c which an orienting platform with three degrees-of-freedom aroung a fixed point located inside the subject's finger. This prototype (a student-realized proof-of-concept) shows that an arbitrary contact in space — complete with the underlying shape, rolling and slip velocities — can be specified independantly of the subject's movement. It is intuitive that in everyday life these mechanics are correlated through the laws of the kinematics of contacts, but in relation to the goals set out in the proposal, it is necessary to develop the apparatuses

capable of disentangling the vast set of possible combinations.

As a simple example, consider Figure 4d. It shows, in symbolic fashion, a finger exploring simple surfaces with different principal curvatures. The arrows symbolize the information available to the perceiver as the result of a slipping contact. It can intuitively be seen that the fundamental properties of the surface can be obtained from homotopic information involving neither position nor speed. The design of this type of machine is very challenging due to their small size, and the need for exacting characteristics form the view point of accuracy and dynamics in relation to human motor and sensory performance, that is exceed it, if the results are to have scientific validy. This apparatus will be built in several variants. With the first variant, it will be it possible to represent the global features of a touched object with a single finger but with a second variant, for same reasons as in the previous section, a two-finger variant will be developed so that subjects can be tested with an opposing grip. Because of the mechanical complexity of a general system able to simulate shapes felt with an opposing grip, it will be retricted to profiles, case that still requires the control of six independent degrees-of-freedom in a restricted space. A third variant with six nominaly co-planar contact surface able to simulate objects of low curvature felt with a single hand will also be constructed. The basic sensing and actuation techniques will be common to these all these variants.

Methodology: Models

This section describes the models and the planned experiments.

Objective 1: Object attributes from multiple sources. Gross shape is an attribute that is now known to be perceived from several sources of information. According to the theory developped by Pont et al. [39, 40] the scale that drives human performance is in essence the scale of the sample that of made of the shape. In other words, scanning with a single finger a shape over a distance that is commensurate with the size of the hand is equivalent to touching it with the whole hand with the difference that it takes more time. However it is still needed to find how different sources of information combine intra-modally.

Basic geometrical considerations set absolute limits on the span of curvatures that can be conveyed by first-order information and some data is known as far as second-order information is concerned [41]. It is therefore to develop a model of how second-order information combines with first-order information, a tasks that will be immensely facilitated by the availabillity of apparatus T used in combination with apparatus G. A leading candidate combination model would be that of maximum likelyhood [42], providing a quantitative model. Similarly it is needed to investigate the force fields combine with first-order geometrical information. The outcome of these experiments will be a model of how the brain computes gross shape.

Compliance has been the subject of several studies including those of Srinivasan and Lamotte [43]. It is proposed that the computational model from which the brain estimate compliance is from skin deformation intra-contact. For the same displacements, different deformations occur due the combined effects of shape and material properties [44]. This account is characteristic of the existence of an inverse problem in the mathematical sense, where compliance can in principle be be obtain from other sources than variations of force and displacement. It will be possible to investigate this hypothesis rigorously with the combined apparatuses T and F. In fact there is strong evidence of this existence of this inverse problem at the level of neural codes [22].

At a small scale, a similar question arises with regard to surface texture. It has been observed many times that the human hand can detect features than are much smaller than what is in principle allowed by the sampling resulting to the distribution of mechanorectors, and this, only if there is slip. To an engineer, this suggest that the haptic system operates like a reconstruction filter that can recover a signal which is not explicitely present in the samples. Apparatuses T and F, because they have been engineered to operate at the required scales in time and space will make the investigation of this question possible. The expected outcome is, again, quantitative, as it will be possible to identify the transfer function of the reconstruction filter.

Objective 2: Role of efference copy. The role of the efference copy, as mentioned, is expected to enable the brain to distinguish self-generated from externally generated motion. This question can be investigated by using apparatus T is in combination with apparatus F. It's been demonstrated that our technique can generate strong sensations of movement on the skin [11, 32], and the same time it is possible to let subject generate their own movement (by setting the force field to zero) or to move without a motor command (by setting the displacement fields), thereby accessing the efference copy. Since it is possible to indepedently control cutaneous inputs, kinesthetic inputs and motor commands, an accurate model of how the brain deals with movement. The described equipment will also allow to investigate a more general question, which is the role of the motor command in perceiving the attributes of shape and compliance. Here apparatus F will be sufficient here. The paradigm is based on observations about the generation of movement. Descending one level of abstraction, it is recalled that the generation of movement is organized as depicted in Figure 5 where the ascending and descending signals are represented [45].

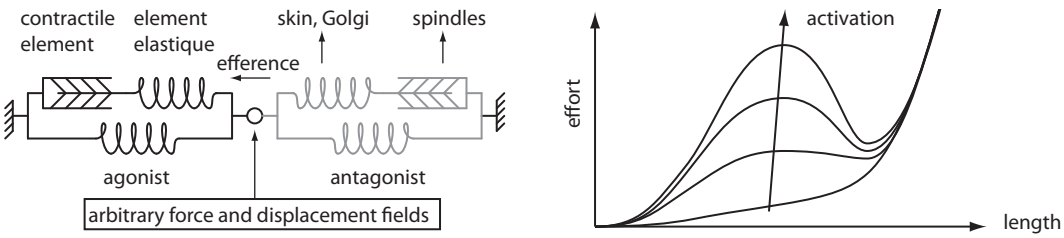


Figure 5: Simplified model of the biomechanical organization of movement generation.

By programming force and displacement fields into the apparatus and asking subjects to interact with them it is possible to tease appart the different sources of information available to the brain. It is known that the motor system has no trouble interating stably with unstable fields [46]. It is therefore possible to selectively modify both the ascending and descending signal, for example by asking the muscle to work harder to maintain an equilibrium while moving it in an arbitrary fashion. In real life these signals are always correlated through the laws of mechanics but here we can control them independently. It is our hypothesis that the efference copy is actually at the origin of the experience of shape and not proprioception [35]. This hypothesis could be tested rigorously. We also believe that this is also the case for the experience of material properties of a touched object: friction and compliance, hypotheses that can be tested using similar methods, and this, would illuminate the ways by which humans 'probe' a plenhaptic function.

Objective 3: Feature detection by the skin. We already commented on the surprising capabilities of the skin, that could have a computational interpretation. In reference [11], we found the strain distribution caused by a pair of traction surfaces. Figure 6a shows the resulting curves for two surfaces 1.2 mm apart at a distance of 1.25 mm inside the surface which shows that normal and shear strains Φ and Ψ respectively and very close to that caused by punch indentation (say a Braille dot).

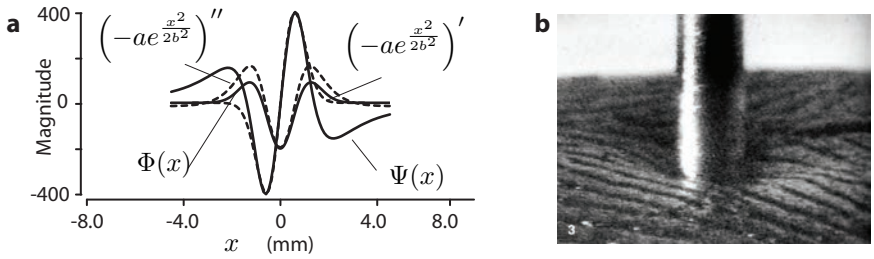


Figure 6: (a) normal (Φ) and shear strain (Ψ) distribution caused by a punch or by localized lateral traction (solid line), second and first derivatives of a Gaussian. (b) Skin deformation under 1 mm punch indentation.

Two observations can be made. The first is that both components of the strain spread far away, 4-times the characteristic distance. The second is that these responses resemble the second and first derivatives of a Gaussian, respectively. In fact, the studies of Cohen et al. [47] clearly show the 'ring-bulge' of the skin when indented (here with a punch twice as large as that considered by us) that spreads a long way like curve $\Phi(x)$. In essence this 'mechanical kernel' convolves with anything we touch. Yet Braille dots (0.5 mm in diameter and 2.5 mm apart) are easily separated; we do no feel the 'bulge', we feel the dots. For the reader familiar with the study of the visual system, these curves are familiar and it is tempting to think that a similar process could occur in touch here small things are detected from zero crossings with the difference that, here, the computation is done by the mechanics. Of course these speculations need verification especially because, as the scale becomes small, the approximation of the skin tissue by a material, even a composite material, becomes increasingly incorrect since; in actuality, it is a complex *structure* probably having emergent properties.

Neverthless we can test the hypothesis that the skin and its innervation detects features rather than 'images'. Like in the study of vision, such investigations can be performed by stuying phenomena of hypeacuity and vernier effects. The first and the simplest can be carried out with apparatus G. Under tightly controlled conditions subjects will be asked to detect the displacement of a contact surface obtained by rolling a plate on the finger at different speeds. It is predicted that displacements smaller than the distance between mechanoreceptors can be detected. Next we will use apparatus T which is ideally suited for this purpose to create a vernier stimulus and ask subject to detect small distances, also as function of frequency. Craig and Jonhson have argued that the two-point discrimination test was not a good way to measure the performance of touch [48], and favored the use of testing for grating orientation. This view certainly agrees with our hypothesis and, again, apparatus T will be ideally suited to test orientation hyperacuity in a hope to demonstrate that the skin is more sensitive to the orientation of features than predicted by inervation density, thereby establishing the role of computations in discriminative touch.

Objective 4: Role of slip. The haptic exploration of objects requires slip. It is known that slip velocity is well estimated by touch [49, 50], and it would be surprising if the brain did not make use of this information. To test the hypothesis that slip has a perceptual role to play we will employ the model illustrated in Figure 7 which is inspired from robotics ideas. Figure 7a symbolizes cutaneous information available to brain showing that both $\boldsymbol{v}_r$ and $\boldsymbol{v}_s$, roll and slip velocities respectively, are sensed in somatotopic coordinates S. At the same time, Figure 7b, variables $\boldsymbol{q} = [q_1, q_2, \ldots, q_n]$ represent generalized coordinates presumably also available to the brain trough kinesthesia that code the state of the finger in space. The finger, F, touches an unknown object at a point, $\boldsymbol{r}$, on the finger that coincides with a point, $\boldsymbol{o}$, on the object. Since all these coordinates can be used to represent smooth manifolds, including the shape of the finger, the kinematics of the arm, the hand, and so-on, there exist Jacobi matrices ${}^{\cdot}J$. that code the various coordinate changes.

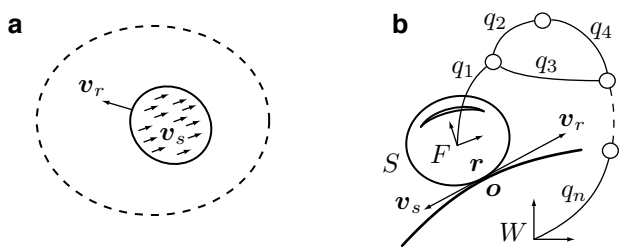


Figure 7: The haptic system seen as a kinematic system.

All calculations done, we can write

$$ {}^{W}J_S\left(\boldsymbol{q}, {}^{S}\boldsymbol{r}(t)\right){}^{S}\boldsymbol{v}_o = {}^{W}J_S\left(\boldsymbol{q}(t), {}^{S}\boldsymbol{r}(t)\right){}^{S}(\boldsymbol{v}_r - \boldsymbol{v}_s) = {}^{F}J_S\left({}^{S}\boldsymbol{r}(t)\right) J_h(\boldsymbol{q}(t))\dot{\boldsymbol{q}}(t). \tag{2} $$

This rather complicated expression actually says something quite simple. It says that through 'kinematic closure', that is, in a system of moving objects all velocities must add-up to zero, which is

equivalent do say that the contact velocity is accessible in two possible ways, in a redundant fashion. Therefore, the task of recovering of trace of point $\boldsymbol{o}$ on the surface of the unknown object can be modeled as:

$$^{W}\boldsymbol{o}(s) = {}^{W}\boldsymbol{o}_0(s) + \int_0^s \left[{}^{W}J_F(\boldsymbol{q}(t)){}^{F}J_S\left({}^{S}\boldsymbol{r}(t)\right)\left({}^{S}(\boldsymbol{v}_r - \boldsymbol{v}_s)\right)\right] \mathrm{d}t, \tag{3}$$

which is a curve parametrized by the arclength s. It can be computed in two different ways from measurements which are made by the haptic system and from *kinematic closure*. This model does not suggest that the curve on the shape is actually computed as per Eq. (3). There are many different ways and in fact, experimental evidence suggest that only certain aspects of it are computed [51], suggesting that the problem is solved in an inverse manner rather than through a direct integral. The availability of apparatus G would allow this hypothesis to be tested since all relevant quantities would be accessible in a disantangled manner. This would also be consistent with the use by the haptic system of global homotopic properties of the interaction of surfaces to enable this process like, in fact, in vision to cite only one seminal article among many [52].

Objective 5: Internalization. Most of the perceptual computations described in the previous paragraph depend crucially on the CNS to have prior knowledge of its own properties as relevant to the solution an any of the problems we have suggested when probing the plenhaptic function of an object. One of the most evident is that to perceive the shape of an object, something that the brain can do haptically just as well as visually [53], the CNS must have internalized the shape of its own anatomy, at least its most relevant aspects. There are several other examples such as the viscolelastic properties of the finger, and so on. This deduction can be tested with the apparatuses that we have described, since having gained control on the most important aspects of haptic interaction, we can modify them to simulate, not different objects, but different hands. This approach would then certainly provide new insights regarding the representation of one-self, although this aspect is somewhat outside the scope of this proposal. Internalization is at the core of the emergence of perceptual constancies.

Objective 6: Conservation of information. Lastly, the applicant proposes to use the described apparatuses to investigate the temporal aspects of haptic perception. These temporal aspects have already been mentioned in the five previous sections but the processing of small-scale feature lends itself to the development of a quantitative model. Combining apparatus T and F it is proposed to model the discrimination of texture as an information processing task. In effect by nature, textures can contain very little information, for example if there are periodic, and to the other extreme, when they are perfectly random and where each scan, each sampling, gives a different realization. We propose to apply this paradigm to measure the haptic information processing capacity and test the hypothesis that indeed, it is constant. Without computer-controlled stimulus generation devices having the appropriate resolution in time and space, such an experiment would be extremely cumbersome to carry out. These experiments will be related to the vernier acuity experiments previously described earlier to obtain spatio-temporal densities of information transfer by the skin. The result will then be matched with published neurophysiogical data regarding the firing rates in tactile afferents [54].

Psychophysics

The psychophysical experiments described in the previous section will be carried out according to well accepted protocols including, as appropriate, scaling methods, determination of points of subjective equivalence, determination of complete psychometric curves by the method of constant stimulus when feasible, or by adaptive methods when appropriate, for instance, to combat the effects of adaptation. In some cases, the method of single stimulus will also be used when the absence of experimental bias is of paramount importance. Standard methods for the analysis of the results will be employed including, signal detection theory, analysis of variance, and classical statistical tests to establish the statistical validity of the results. As appropriate, due to the nature of the data, the results will be analyzed using Bayesian statistical methods (likelihood) rather than more classical frequency-based methods. The applicant has a history of consulting or collaborating with experts in psychophysical methods and using the services of statistics experts when needed.

Other Projects

This project has relationships with a number of other projects, past and on-going, in Europe and in the rest of world. First, there is the Enactive Network of Excellence with which the applicant was associated through funding in Canada (now completed, see applicant's CV) and where he also participated as an invited speaker. There is also the now completed FP6 TOUCH-HAPSYS project which has spawn a large number of results, and the on-going FP6 Specific Targeted Research Nanobiotact Project which has close connections with the proposed research. There are also more applied projects, namely the completed MICOLE project to address the needs of blind and visually impaired, the also completed project HapTex on the simulation of fabrics. Currently the applicant is part of the consortium of the FP7 NIW where the objective to simulate walking grounds in multimodal manner. The applicant's workpackage is concerned mostly with the design and deployments of haptic stimulators embedded in shoes for use in virtual environments games and rehabilitation applications.

Applicant's Collaborators Relevant to this Project

The applicant has a history of seeking the collaboration of specialists of related domains. In the recent past, and of special relevance to this project, the applicant has enjoyed fruitful and productive collaboration with the following individuals (all concretized by one of several co-authored articles published, in press, or submitted):

- Allan M. Smith, head of the Department of Physiology, Université of Montréal who is specialist of the neurophysiology and neuroanatomy of the hand as well as of motor and sensory central physiology in humans and monkeys;
- C. Elaine Chapman, also of the Department of Physiology, Université de Montréal who is a specialist of the somatosensory system and systems neuroscience;
- Jean-Louis Thonnard of the Unité de réadaptation et de médecine physique, Université Catholique de Louvain.
- Christopher I. Moore of the McGovern Institute for Brain Research at MIT who is a specialist of the neural organization related to the perceptual function including the cortical areas relevant to tactile perception;
- Mark Wexler of the Laboratoire de la Psychology de la Perception, Université Paris Descartes who is a specialist of vision perception, will be co-investigator in the proposed project;
- M. O. Ernst of the Max Planck Institute for Biological Cybernetics who is a specialist of human perception with a focus on multimodal integration and visual-haptic interaction;
- Astrid M. L. Kappers of the Helmholtz Institute, Utrecht University who is a specialist of human haptic and visual perception;
- Hannah Michalska of the Department of Electrical and Computer Engineering, McGill University, who is specialist of nonlinear systems and optimization. H. Michalska is also a mathematician who enjoys an "Erdös number" of 4.

iii. Resources

The following tables sumarizes the resources needed to carry out the project. An essential component of the human resources is a research engineer given the amount of high-performance electromechanical hardware to be developed. In the past 10 years all the apparatuses needed for the research were entirely designed and constructed by the applicant and his coworkers, with occasional help from the departmental machinists. On the whole, neverthless, the majority of the equipment was manufactured in the laboratory with simple machine tools or produced by commercial machine shops.

The new laboratory at UPMC benefits machining facilities and a rapid prototyping machine, but some of the more specialized parts will have to be manufactured outside when they involve specialized fabrication processes where electro-erosion, water jet and laser cutting are anticipated. In the first year, funding is requested for the purchase of control hardware. In the subsequent years the requested funding will enable the group to have a new generation of magnetically actuated tactile displays as described in the proposal. We anticipate the need to purchase a number of basic laboratory equipments, including an optical microscope with microimaging camera, a signal analyser, a precision grinder, an oscilloscope and the like. There is need to provide the group with a computing infrastructure. The rest of the requested funding is essentially dedicated to the salaries of the personnel needed to carry out a program of this magnitude with a balance of postdoc fellows and graduate students. Provision is made also in the budget to fund two undergraduate interns as a talent recruitment mechanism. Vincent Hayward will manage the project and supervise the personnel indicated in following Table 1. Mark Wexler will collaborate with Vincent Hayward in the studies that require expertise in psychophysics methods and theories and supervise the personnel indicated below.

iv. Resources concerned with the project extension months 55–72

The reason of the delay is that we have had difficulties completing the development one of the five apparatuses needed for the program, but which is now just come operational. Completion of this step is essential for an efficient transition to the Proof-of-Concept research and development program (ERC-PoC-2014, RELAX, No. 665595). In the completion of the remaining experiments, since no major equipment needs to acquired, the remaining funds would be mostly allocated to the salaries of post-docs. It must be noted that the following Table 1 'expenses to date' are underestimates owing to accounting delays. The extension has no impact on the work conducted at CNRS and hence there is no budget allocated to CNRS in the remaining period.

Part of the personnel expenses will concern work done at CNRS. For these expenses, the allocated funds are 265 000 € for the full duration of the project. There will be no other expenditures by this partner. For period three, the CNRS expenditures were of 75 321.85 €. The CNRS anticipates to spend 54 000.00 € for period four.

Table 1: **Amended** Combined UPMC and CNRS budget breakdown in €

Cost categories	1–18	19–36	37–54	55–72	Total
1.1 Personnel salaries					
PI @ 60% effort	110 543.16	122 158.39	113 808.24	110 000.00	456 869.79
Senior Staff	210 293.96	4 849.38	21 603.25	25 000.00	261 746.59
Post Docs	122 019.55	207 093.08	79 501.65	100 000.00	508 614.28
Students	6 120.63	29 577.29	32 198.84	20 000.00	87 896.76
Other	7 695.00	93 716.86	167 927.41	20 000.00	289 339.27
Total salaries	456 672.28	457 755.89	415 039.39	275 000.00	1 604 466.69
1.2 Costs other than salaries					
Equipment	6 968.95	36 198.52	38 490.39	37 000.00	118 657.86
Consumables & Machining	48 202.42	27 730.10	22 557.18	20 000.00	118 489.70
Travel	19 622.27	22 601.83	4 501.66	5 599.00	52 324.93
Publication costs	0.00	0.00	7 413.25	0.00	7 413.25
Other	4 578.57	9 548.17	0.00	0.00	14 126.74
Total other than salaries	79 372.21	96 078.62	72 962.48	62 599.29	319 513.60
1.3 Total Direct Costs	536 044.52	553 833.62	488 001.87	337 599.17	1 915 479.17
1.4 Overhead 20% on direct costs	107 207.90	110 766.72	97 600.37	67 519.83	383 095.83
1.5 Audit subcontract	3 425.00	0.00	0.00	0.00	3 425.00
1.6 Requested Grant	646 678.41	664 600.34	585 602.25	405 119.00	2 302 000.00

Table 2: **Amended** resource allocation

Intermediate goal	Estimated % of total grant	Expected completion	Comment
Objective 1	15	50	requires App. T+G, App. T+F
Objective 2	10	24	requires App. T+F
Objective 3	10	30	requires App. G+T
Objective 4	8	36	requires App. G
Objective 5	10	65	requires App. G
Objective 6	8	45	requires App. T+F
Apparatus T	15	12	Technically more challenging, work on it first
Apparatus F	10	18	Exacting characteristics required
Apparatus G	14	24	Exacting characteristics required

iv. Ethical Issues

Ethical issues table.

	Research on Human Embryo/Foetus	YES	NO
	Does the proposed research involve human Embryos?		✓
	Does the proposed research involve human Foetal Tissues/ Cells?		✓
	Does the proposed research involve human Embryonic Stem Cells (hESCs)?		✓
	Does the proposed research on human Embryonic Stem Cells involve cells in culture?		✓
	Does the proposed research on Human Embryonic Stem Cells involve the derivation of cells from Embryos?		✓
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		✓

	Research on Humans	YES	NO
	Does the proposed research involve children?		✓
	Does the proposed research involve patients?		✓
	Does the proposed research involve persons not able to give consent?		✓
	Does the proposed research involve adult healthy volunteers?	✓	
	Does the proposed research involve Human genetic material?		✓
	Does the proposed research involve Human biological samples?		✓
	Does the proposed research involve Human data collection?		✓
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?	✓	

	Privacy	YES	NO
	Does the proposed research involve processing of genetic information or personal data (e.g. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?		✓
	Does the proposed research involve tracking the location or observation of people?		✓
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		✓

	Research on Animals	YES	NO
	Does the proposed research involve research on animals?		✓
	Are those animals transgenic small laboratory animals?		✓
	Are those animals transgenic farm animals?		✓
	Are those animals non-human primates?		✓
	Are those animals cloned farm animals?		✓
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		✓

	Research Involving Developing Countries	YES	NO
	Does the proposed research involve the use of local resources (genetic, animal, plant, etc)?		✓
	Is the proposed research of benefit to local communities (e.g. capacity building, access to healthcare, education, etc)?		✓
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		✓

	Dual Use	YES	NO
	Research having direct military use		✓
	Research having the potential for terrorist abuse		✓
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		✓

Other Ethical Issues	YES	NO
Are there OTHER activities that may raise Ethical Issues?		✓
If YES please specify:		

References

[1] D. Marr. *Vision*. Freeman New York, 1982.

[2] R. L. Klatzky and S. J. Lederman. Toward a computational model of constraint-driven exploration and haptic object identification. *Perception*, 22(5):597–621, 1993.

[3] H. Y. Solomon and M. T. Turvey. Haptically perceiving the distances reachable with hand-held objects. *Journal of Experimental Psychology: Human Perception and Performance*, 14(3):404–427, 1988.

[4] M. O. Ernst and M. S. Banks. Human integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415:429–433, 2002.

[5] J.M. Hillis, M. O. Ernst, M. S. Banks, and M. S. Landy. Combining sensory information: Mandatory fusion within, but not between senses. *Science*, 298(5598):1627–1630, 2002.

[6] D. Goldreich. A bayesian perceptual model replicates the cutaneous rabbit and other spatiotemporal illusions. *PLoS One*, 2(3):e333, 2007.

[7] R. S. Fearing and J. M. Hollerbach. Basic solid mechanics for tactile sensing. *International Journal of Robotics Research*, 4:40–54, 1985.

[8] N. J. Ferrier and R. W. Brockett. Reconstructing the shape of a deformable membrane from image data. *International Journal of Robotics Research*, 19(9):795–816, 2000.

[9] A. Bicchi, E. P. Scilingo, E. Ricciardi, and P. Pietrini. Tactile flow explains haptic counterparts of common visual illusions. *Brain Research Bulletin*, 75(6):737–741, 2008.

[10] R. Kikuuwe, A. Sano, H. Mochiyama, N. Takesue, and H. Fujimoto. Enhancing haptic detection of surface undulation. *ACM Transactions on Applied Perception*, 2(1):46–67, 2005.

[11] Q. Wang and V. Hayward. Tactile synthesis and perceptual inverse problems seen from the view point of contact mechanics. *ACM Transactions on Applied Perception*, 5(2):1–19, 2008.

[12] L. R. Harmon. Automated tactile sensing. *The International Journal of Robotics Research*, 1(3):3–32, 1982.

[13] L. Beccai, S. Roccella, L. Ascari, P. Valdastri, A. Sieber, M. C. Carrozza, and P. Dario. Development and experimental analysis of a soft compliant tactile microsensor for anthropomorphic artificial hand. *IEEE/ASME Transactions on Mechatronics*, 13(2):158–168, 2008.

[14] D. De Rossi, A. Nannini, and C. Domenici. Artificial sensing skin mimicking mechanoelectrical conversion properties of human dermis. *IEEE Transactions on Biomedical Engineering*, 35(2):83–92, 1988.

[15] W. D. Hillis. A high-resolution imaging touch sensor. *International Journal of Robotics Research*, 1(2):33–44, 1982.

[16] L. Ascari, U. Bertocchi, P. Corradi, C. Laschi, and P. Dario. Bio-inspired grasp control in a robotic hand with massive sensorial input. *Biological Cybernetics*, 100(2):109–128, 2008.

[17] K. Kim, J. E. Colgate, and A. Makhlin M. A. Peshkin, J. J. Santos-Munne. A miniature tactor design for upper extremity prosthesis. In *Proceedings of the Frontiers in the Convergence of Bioscience and Information Technologies*, pages 537–542, 2007.

[18] N. Cauna. Nature and functions of the papillary ridges of the digital skin. *The Anatomical Record*, 119:449–468, 1954.

[19] J. R. Phillips and K. O. Johnson. Tactile spatial resolution. III. a continuum mechanics model of skin predicting mechanoreceptor responses to bars, edges, and gratings. *Journal of Neurophysiology*, 46:1204–1225, 1981.

[20] M. A. Srinivasan, J. M. Whitehouse, and R. H. LaMotte. Tactile detection of slip: surface microgeometry and peripheral neural codes. *Journal of Neurophysiology*, 63(6):1323–1332, 1990.

[21] M. A. Srinivasan and K. Dandekar. An investigation of the mechanics of tactile sense using two-dimensional models of the primate fingertip. *Journal of Biomechanical Engineering*, 118(1):48–55, 1996.

[22] R. S. Johansson and I. Birznieks. First spikes in ensembles of human tactile afferents code complex spatial fingertip events. *Nature Neuroscience*, 7(2):170–177, 2004.

[23] V. Hayward. Haptic shape cues, invariants, priors, and interface design. In M. Grunwald, editor, *Human Haptic Perception – Basics and Applications*, chapter 31, pages 381–392. Birkhauser Verlag, 2008.

[24] S. J. Bensmaïa, J. C. Craig, and K. O. Johnson. Temporal factors in tactile spatial acuity: Evidence for ra interference in fine spatial processing. *Journal of Neurophysiology*, 95:1783–1791, 2006.

[25] M. Fahle and T. Poggio. Visual hyperacuity: Spatiotemporal interpolation in human vision. *Proceedings of the Royal Society of London, Series B, Biological Sciences*, 231(1193):451–477, 1981.

[26] O. Carter, T. Konkle, Q. Wang, V. Hayward, and C. I. Moore. Tactile rivalry demonstrated with an ambiguous apparent-motion quartet. *Current Biology*, 18(14):1050–1054, 2008.

[27] I. Fasiello, V. Hayward, G. Campion, and M. Wexler. A haptic size illusion and its near absence in the blind. *Submitted*, 2009.

[28] V. Hayward and M. Cruz-Hernandez. Tactile display device using distributed lateral skin stretch. In *Proceedings of the Haptic Interfaces for Virtual Environment and Teleoperator Systems Symposium*, volume DSC-69-2, pages 1309–1314. ASME, 2000.

[29] Q. Wang and V. Hayward. Compact, portable, modular, high-performance, distributed tactile transducer device based on lateral skin deformation. In *Proceedings of the Symposium on Haptic Interfaces For Virtual Environment And Teleoperator Systems*, pages 67–72, 2006.

[30] Q. Wang and V. Hayward. In vivo biomechanics of the fingerpad skin under local tangential traction. *Journal of Biomechanics*, 40(4):851–860, 2007.

[31] G. Petit, A. Dufresne, V. Levesque, and V. Hayward. Exploration multimodale d'images pour des utilisateurs ayant une déficience visuelle. *Science et Technology pour le Handicap*, 2(3):175–186, 2008.

[32] T. Konkle, Q. Wang, V. Hayward, and C. I. Moore. Motion aftereffects transfer between touch and vision. *Current Biology*, 19(9):745–750, 2009.

[33] G. Campion and V. Hayward. Fundamental limits in the rendering of virtual haptic textures. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 263–270, 2005.

[34] G. Campion, Q. Wang, and V. Hayward. The Pantograph Mk-II: A haptic instrument. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS'05*, pages 723–728, 2005.

[35] G. Robles De La Torre and V. Hayward. Force can overcome object geometry in the perception of shape through active touch. *Nature*, 412:445–448, 2001.

[36] A. M. Smith, C. E. Chapman, F. Donati, P. Fortier-Poisson, and V. Hayward. Perception of simulated local shapes using active and passive touch. *Journal of Neurophysiology*, 102:3519–3529, 2009.

[37] H. Dostmohamed and V. Hayward. Trajectory of contact region on the fingerpad gives the illusion of haptic shape. *Experimental Brain Research*, 164(3):387–394, 2005.

[38] M. W. A. Wijntjes, A. Sato, V. Hayward, and A. M. L. Kappers. Local surface orientation dominates haptic curvature discrimination. *IEEE Transactions on Haptics*, 2(2):94–102, 2009.

[39] S. C. Pont, A. M. L. Kappers, and J. J. Koenderink. Haptic curvature discrimination at several regions of the hand. *Perception and Psychophysics*, 59(8):1225–1240, 1997.

[40] S. C. Pont, A. M. L. Kappers, and J. J. Koenderink. Similar mechanisms underlie curvature comparison by static and dynamic touch. *Perception and Psychopysics*, 61(5):874–894, 1999.

[41] A. W. Goodwin, K. T. John, and A. H. Marceglia. Tactile discrimination of curvature by humans using only cutaneous information from the fingerpads. *Experimental Brain Research*, 86:663–672, 1991.

[42] K. Drewing and M. O. Ernst. Integration of force and position cues for shape perception through active touch. *Brain Research*, 1078:92—100, 2006.

[43] M. A. Srinivasan and R. H. LaMotte. Tactual discrimination of softness. *Journal of Neurophysiology*, 73:88–101, 1995.

[44] A. Bicchi, E. P. Scilingo, and D. De Rossi. Haptic discrimination of softness in teleoperation: the role of the contact area spread rate. *IEEE Transactions on Robotics and Automation*, 16(5):496–504, 2008.

[45] D. A. Winter. *Biomechanics and Motor Control of Human Mouvement*, chapter Muscle Mechanics. Wiley, 1990.

[46] E. Burdet, R. Osu, D. W. Franklin, T. E. Milner, and M. Kawoto. The central nervous system stabilizes unstable dynamics by learning optimal impedance. *Nature*, 6862:446–449, 2001.

[47] J. C. Cohen, J. C. Makous, and S. J. Bolanowski. Under which conditions do the skin and probe decouple during sinusoidal vibrations? *Experimental Brain Research*, 129(w):211–217, 1999.

[48] J. C. Craig and K. O. Johnson. The two-point threshold: Not a measure of tactile spatial resolution. *Current Directions in Psychological Science*, 9:29–32, 2000.

[49] G. K. Essick, O. Franzen, and B. L. Whitsel. Discrimination and scaling of velocity of stimulus motion across the skin. *Somatosensory Motor Research*, 6(1):21–40, 1988.

[50] A. Dépeault, E. M. Meftah, and C. E. Chapman. Tactile speed scaling: contributions of time and space. *Journal of Neurophysiology*, 99:1422–1434, 2008.

[51] A. F. J. Sanders and A. M. L. Kappers. Curvature affects haptic length perception. *Acta Psychologica*, 129(3):340–351, 2008.

[52] J. J. Koenderink and A. J. van Doorn. The internal representation of solid shape with respect to vision. *Biological Cybernetics*, 32(4):211–216, 1979.

[53] J. F. Norman, H. F. Norman, A. M. Clayton, J. Lianekhammy, and G. Zielke. The visual and haptic perception of natural object shape. *Perception & Psychophysics*, 66(2):342–351, 2004.

[54] Å. V. Vallbo and R. S. Johansson. Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. *Human Neurobiology*, 3:3–14, 1984.

PI's Host institution

The research is to take place at the *Institut des Systèmes Intelligent et de Robotique* (ISIR), newly created at the Université Pierre et Marie Curie (UMPC), administratively labelled Paris 6, in the heart of Paris, France. UMPC is arguably the leading science and medicine University in France where it consistently ranks first among the French Universities according to most international ranking bodies. UMPC hosts 3500 doctoral students and seven training and research units (UFR) in chemistry, engineering, mathematics, medicine, physics, sciences of life, earth sciences, environement and biodiversity. It also hosts an engineering school (Polytech'Paris), the Institut d'astrophysique de Paris, the Institut Henri Poincaré, and 3 marines stations at Roscoff, Banyuls and Villefranche-sur-Mer that have marine life observatories.

ISIR was founded in 2007 from the grouping of three UMPC laboratories, namely, the *Laboratoire de Robotique de Paris*, the *Groupe Perception et Réseaux Connexionnistes* and the *Laboratoire des Instruments et Systèmes d'Ile de France, quipe AnimatLab du Laboratoire dInformatique de Paris 6*. Today, ISIR is a major research unit and a major player in the engineering UFR of UMPC. It is associated with CNRS through the *Sciences et Technologies de l'Information et de l'Ingénierie* department. ISIR is a multidisciplinary laboratory with activities in complex mechanical systems, systems and control, and signal and image processing. ISIR hosts three divisions: Interactive Systems, Perception and Human Mouvement, and Integrated Mobile and Autonomous Systems. The Institute has ten full professors, twenty associate professors and about sixty graduate students occupying newly renovated space on the Jussieu Campus in the Paris Latin Quarter, including nearly 4 000 m^2 of new laboratory space. ISIR became an UMR in 2008 (7222).

Additional institutions

The Laboratoire Psychologie de la Perception (LPP) directed by J. Kevin ORegan was officially founded by the CNRS in January 2006. At that time it comprised 14 CNRS scientists, 5 Paris Descartes associate and full professors, 6 technical staff and 33 graduate students and post-docs grouped in four teams. Three of those teams in more or less their present form emanated from two distinct CNRS structures (the Laboratoire de *Psychologie Exprimentale and the Laboratoire Cognition et Dveloppement*) located at the Institut de Psychologie at Boulogne Billancourt. These two structures ceased to exist in December 2005. A fourth team (Audition) comprises a former member of the *Laboratoire de Psychologie Exprimentale*, and two members of the CNRS unit "Sciences et Technologie de la Musique et du Son". In January 2007 LPP became a UMR (8158).