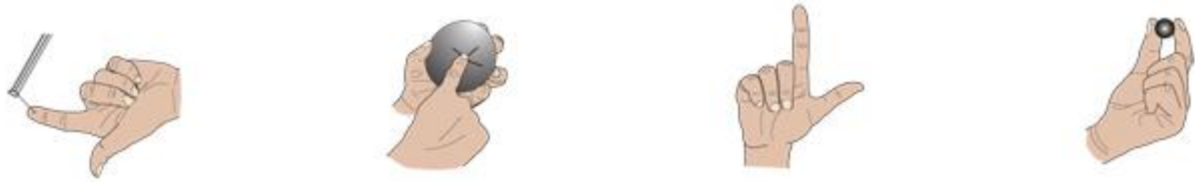


THE TOUCH LABORATORY

Scope of Research Programme:

Basic research in the Touch Lab has focused for many years now on the sense of touch in humans. The work has examined how people learn about the world around them through haptic exploration and manipulation. Topics have included, for example,

- the haptic perception of object and surface properties (e.g., texture, hardness, thermal properties, shape, size, weight, function, etc.)
- the haptic recognition and identification of common and unfamiliar multidimensional objects by children, young adults, and older adults
- the "haptic glance": relative availability of properties of surfaces and objects during early haptic processing
- the nature and role of manual exploration
- haptic space perception in the sighted and the blind
- intersensory integration and multimodal perception (vision, audition and touch)
- perceiving objects and surface properties through an intermediate probe
- haptic face processing of identity and emotions by blindfolded sighted, prosopagnosic, and blind individuals
- sensory-guided motor control of prehension, with and without vision.

Behavioural approaches typically include a variety of psychophysical, perceptual and cognitive procedures, the classification of videotaped hand movements that accompany manual exploration during haptic search, response latencies, errors, oral/written questionnaire responses, and kinematic and dynamic measures of hand/arm movements.

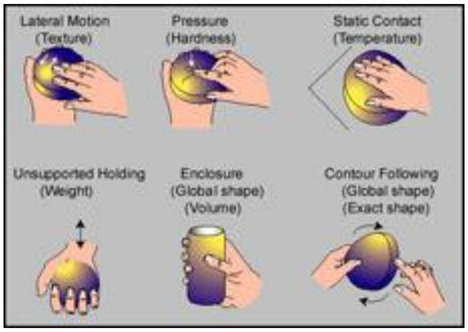
Neuroscience approaches include the use of fMRI (functional magnetic resonance imaging procedures) to study brain activation during the performance of various tasks in real time, and the participation of both neurologically intact and neurologically impaired populations (e.g., congenitally blind, blind diabetic, prosopagnosic).

Some of the applications of this work include:

- the design of tangible graphics for the blind (e.g., raised maps, pictures, graphs, etc.)
- the design of a raised tactile texture feature and tactile code that enable blind individuals to denominate the new Canadian banknotes by touch
- the behavioural assessment of sensorimotor hand function following peripheral nerve damage (e.g., from diabetes, accident, etc.) and consequent surgical repair
- the design of tactile or haptic sensing systems for autonomous robots equipped with tactile, force and position sensors embedded in robotic end effectors
- the design of a tactile shape display using RC servomotors
- the design of haptic interfaces for teleoperation and virtual environment systems involving the participation of a human operator in the control loop. Broadly speaking, my work addresses the capabilities and limitations of the human haptic system, from sensory/perceptual, cognitive and motor perspectives. Such information is critical in designing haptic interfaces that can be efficiently and comfortably controlled by the

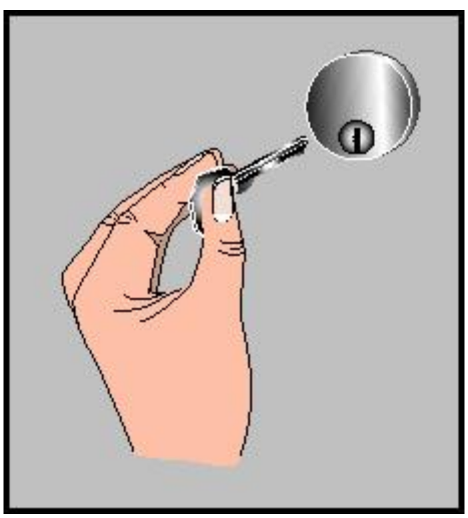
operator (e.g., e-commerce, e-communication). In addition, our work offers scientifically-based methods for evaluating actual performance with haptic interface systems
- rendering virtual textures for use in virtual-environment applications.

Examples of Research Projects:



Haptics

- haptic perception, recognition and identification of objects and their properties
- haptic processing of identity and location from a "haptic glance"
- haptic space perception in the sighted and the blind
- haptic perception of surfaces and objects with a rigid probe
- manual exploration in young children
- human hand function
- haptic face processing
- fMRI studies on tactile/haptic processing of objects and their properties
- haptic perceptual organization in haptic perception and grasping
- haptic vs. visual mental body representations



Sensory-guided Motor Control

- the role of vision in manipulating a familiar object
- anticipating torques produced by lifting and moving objects
- the independence of perception and action channels

Haptic Interfaces for Teleoperation and Virtual Environment Systems

- creation and psychophysical assessment of virtual haptic textures
- designing haptic interfaces: assessing the need for spatially distributed forces to the fingertips
- a tactile shape display

Lederman, S.J. & Klatzky, R.L. (2009). ***Haptic perception: A tutorial*.** Attention, Perception, &Psychophysics. 71 (7), 1439-1459.

Abstract
This tutorial focuses on the sense of touch within the context of a fully active human observer. It is intended for graduate students and researchers outside the discipline who seek an introduction to the rapidly evolving field of human haptics. The tutorial begins with a review of peripheral sensory receptors in skin, muscles, tendons, and joints. We then describe an extensive body of research on “what” and “where” channels, the former dealing with haptic perception of objects, surfaces, and their properties, and the latter with perception of spatial layout on the skin and in external space relative to the perceiver. We conclude with a brief discussion of other significant issuesin the field, including vision–touch interactions, affective touch, neural plasticity, and applications.

Lederman, S.J. & Klatzky, R.L. (2004). ***Haptic Identification of Common Objects: Effects of Constraining the Manual Exploration Process.*** Perception & Psychophysics, 66(4) , 618-628.

Abstract
In this paper we address the effects on haptic recognition of common objects when manual exploration is constrained by using two kinds of rigid links, sheaths (Experiment 1a) and probes (Experiments 1b and 2). The collective effects of five different constraints are considered, including three from previous research (Klatzky, Loomis, Lederman, Wake & Fujita, 1993): reducing the number of end effectors, wearing a compliant finger cover, and splinting the fingers, and from two current constraints: wearing a rigid finger sheath and using a rigid probe. The resulting impairments are interpreted in terms of the loss of somatosensory information from cutaneous and/or kinesthetic inputs. In addition, we relate the results to the design of haptic interfaces for teleoperation and virtual environments, which share some of the same reduction of sensory cues that we have produced experimentally.

Lederman, S.J., & Klatzky, R.L. (1987). ***Hand movements: A window into haptic object recognition.*** Cognitive Psychology, 19(3), 342-368.

Abstract
Two experiments establish links between desired knowledge about objects and hand movements during haptic object exploration. Experiment I used a match-to-sample task, in which blindfolded subjects were directed to match objects on a particular dimension (e.g.. texture). Hand movements during object exploration were reliably classified as "exploratory procedures," each procedure defined by its invariant and typical properties. The movement profile. i.e.. the distribution of exploratory procedures was directly related to the desired object knowledge that was required for the match. Experiment 2 addressed the reasons for the specific links between exploratory procedures and knowledge goals. Hand movements were constrained, and performance on various matching tasks was assessed. The procedures were considered in terms of their necessity, sufficiency and optimality of performance for each task. The results establish that in free exploration, a procedure is generally used to acquire information about an object property, not because it is merely sufficient, but because it is optimal or even necessary. Hand movements can serve as "windows," through which it is possible to learn about the underlying representation of objects in memory and the processes by which such representations are derived and utilized.

Klatzky, R., **Lederman, S.J.,** & Reed, C. (1987). ***There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision.*** Journal of Experimental Psychology: General, 116(4), 356-369.

Abstract

The availability and salience of object attributes under haptic exploration, with and without vision, were assessed by two tasks in which subjects sorted objects that varied factorially in size, shape, texture, and hardness. In the directed-discrimination task, subjects were instructed to sort along a particular dimension. Although levels on all dimensions were easily discriminated, shape was relatively less so for haptic explorers without vision, as was hardness for those using vision and haptics. Size was least discriminate for both groups. In the free-sorting task, subjects were to sort objects by similarity. Three groups used haptic exploration only; these were differentiated by the experimenters' definition of object similarity: unbiased haptics (no particular definition of similarity), haptically biased haptics (similarity = objects feel similar), haptics plus visual imagery (similarity = objects' visual images are similar). A fourth group used vision as well as haptics, with instructions like those of the unbiased haptics group. Dimensional salience was measured by the extent to which levels on a dimension were differentiated in free sorting (more differentiation indicating higher salience). The unbiased haptics and haptically biased haptics groups were highly similar, both found the substance dimensions (hardness and texture) relatively salient. The haptics plus visual imagery group showed shape to be overwhelmingly salient, even more so when they were instructed to use two hands, but less so when they had just seen the objects. The haptics plus vision group showed salience to be more evenly distributed over the dimensions. Exploratory hand movements were videotaped and scored into four categories of exploratory procedure (Lederman & Klatzky, 1987): lateral motion, pressure, contour following, and enclosure (related to texture, hardness, shape, and size, respectively). The distribution of exploratory procedures was found to be directly related to both the designated dimension in the directed-discrimination task, and the salient dimension in the free-sorting task. The results support our contention that the haptic and visual systems have distinct encoding pathways, with haptics oriented toward the encoding of substance rather than shape. This may reflect a direct influence of haptic exploratory procedures: The procedures that are executed under unbiased haptic encoding are those that are generally found to be rapid and accurate (high "ease of encoding"), and the execution of these procedures determines which object properties become salient.

Klatzky, R.L., **Lederman, S.J.,** & Metzger, V. (1985). ***Identifying objects by touch: An "expert system".*** Perception & Psychophysics, 37(4), 299-302.

Abstract

How good are we at recognizing objects by touch? Intuition may suggest that the haptic system is a poor recognition device, and previous research with nonsense shapes and tangible-graphics displays supports this opinion. We argue that the recognition capabilities of touch are best assessed with three-dimensional, familiar objects. The present study provides a baseline measure of recognition under those circumstances, and it indicates that haptic object recognition can be both rapid and accurate.

Purdy, K.A., **Lederman, S.J.,** & Klatzky, R.L. (2004). ***Haptic processing of the location of a known property: Does knowing what you've touched tell you where it is?*** Canadian Journal of Psychology, 58, 32-45.

Abstract
The relationship between knowing where a haptic property is located and knowing what it is was investigated using a haptic-search paradigm. Across trials, from 1 to 6 stimuli were presented simultaneously to varying combinations of the middle three fingertips of both hands. Subjects reported the presence/absence of a target or its location for 4 perceptual dimensions: rough/smooth, edge/no edge, relative position (right/left), and relative orientation (right/left). Reaction time data were plotted as a function of set size. The slope data indicated no difference in processing load for location as compared to identity processing. However, the intercept data did reveal a cost associated with processing location information. Location information was not obtained for "free" when identity was processed. The data also supported a critical distinction between material and edge dimensions versus geometric dimensions, as the size of the cost associated with processing location was larger for spatial than for intensive stimuli.

Lederman, S.J., Klatzky, R.L. (1997). ***Relative availability of surface and object properties during early haptic processing.*** Journal of Experimental Psychology: Human Perception and Performance, 23(6), 1-28.

Abstract
How the relative order in which 4 property classes of haptically perceived surfaces becomes available for processing after initial contact was studied. The classes included material, abrupt-surface discontinuity, relative orientation and continuous 3-D surface contour properties. Relative accessibility was evaluated by using the slopes of haptic search functions obtained with a modified version of A. Treisman's (Treisman & Gormican, 1988) visual pop-out paradigm: the yo intercepts were used to confirm and finetune order of accessibility. Target and distractors differed markedly in terms of their value on a single dimension. The results of 15 experiments show that coarse intensive discriminations are haptically processed early on. In marked contrast, most spatially encoded dimensions become accessible relatively later, sometimes considerably so

Klatzky, R.L., & **Lederman, S.J.** (1995). ***Identifying objects from a haptic glance.*** Perception and Psychophysics, 57(8), 1111-1123.

Abstract
Subjects identified common objects under conditions of a “haptic glance,” a brief haptic exposure that placed severe spatial and temporal constraints on stimulus processing. They received no advance cue, a superordinate-level name as cue, or a superordinate and basic-level name as cue. The objects varied in size relative to the fingertip and in the most diagnostic attribute, either texture or shape. The data suggest that object recognition can occur when global volumetric primitives cannot directly be extracted. Even with no cue, confusion errors resembled the target object and indicated extraction of material and local shape information, which was sufficient to provide accuracy above 20%. Performance improved with cuing, and the effect of exposure duration was observed primarily with minimal cuing, indicating compensatory effects of top-down processing.

Barber, P., & **Lederman S.J.** (1988). ***Encoding direction in manipulatory space and the role of visual experience.*** Journal of Visual Impairment and Blindness, 82(3), 99-106.

Abstract
Congenitally blind, adventitiously blind, and blindfolded sighted adults made direction estimates of target position within manipulatory space after their index fingers were guided to each target from a neutral starting point. Observers remained seated in the same location throughout the experiment. In a "finger-movement" condition, observers' fingers were guided to a target location from which they pointed to each of the other targets. In an "imagination" condition, the observers pretended they were at one of the target locations and pointed to the other targets as is they occupied the new target position. Regardless of visual experience, observers in the finger-movement task were more accurate but only negligibly faster than in the imagination task. The subjective reports of all groups suggested that cognitive-mapping heuristics were used in both tasks, contrasting with previous results obtained in ambulatory space (Rieser,Guth, & Hill, 1982). The results are considered in the light of a fundamental difference between manipulatory and ambulatory space.

Lederman, S.J., Klatzky, R.L., Collins, A., & Wardell, J. (1987). ***Exploring environments by hand or foot: Time-based heuristics for encoding distance in movement space.*** Journal of Experimental Psychology: Learning, Memory, & Cognition, 13(4), 606-614.

Abstract
In Experiment I, blindfolded observers judged (a) the distance of pathways felt by hand and (b) the straight-line distance between pathway endpoints inferred from such exploration. In Experiment 2, blindfolded observers made corresponding estimates after traversing similar pathways on foot. Pathways were explored under three different speeds. Under both manipulatory and ambulatory exploration, there was substantial length distortion of inferred distance: The straight-line distance was increasingly overestimated with increases in the length of the explored pathway. With manipulatory exploration, slower movements increased length distortion, but duration effects proved secondary to effects of spatial extent. For ambulatory exploration, no duration effects were obtained. Observers used time-independent heuristics, that is, a footstep metric for estimating the pathway actually travelled and a spatial imaging strategy for estimating the inferred line between pathway endpoints. The studies establish length distortion as a general phenomenon in movement space and identify its major causes as spatial rather than temporal.

Lederman, S.J., Klatzky, R.L., & Barber, P.O. (1985). ***Spatial and movement-based heuristics for encoding pattern information through touch.*** Journal of Experimental Psychology: General, 114, 33-49.

Abstract
Seven experiments investigated the heuristics people use to encode spatial patterninformation through touch. Observers traced a tangible pathway with one hand and then answered questions about either the euclidean line between the pathway endpoints or the pathway itself. Parameters of the euclidean line were held constant, while characteristics of the felt pathway were manipulated. Experiments 1-4 showed that blindfolded sighted and blind observers increasingly overestimated the length of the euclidean line as the length of the explored pathway increased. This indicates a movement-based heuristic for encoding distance. Experiments 5-7 indicated that judgments of the position of the euclidean line did not vary with the position of the felt pathway or the extent to which it deviated from that line. Instead, the results indicated that observers relied on implicit spatial axes, which are movement independent, to judge position. These and other results have implications for theories of haptic encoding of spatial pattern and for the construction of tangible graphics displays.

Lederman, S.J., Klatzky, R.L., Hamilton, C.L. & Ramsay, G.I. (1999). ***Perceiving roughness via a rigid probe: Psychophysical effects of exploration speed and mode of touch.*** Haptics-e, 1(1).

Abstract

Two experiments investigated the psychophysical consequences for roughness perception of altering the speed of motion with which real textured surfaces are explored using a rigid probe. Two speed ranges were used: a 10-fold change (Experiment 1) and a 4-fold change (Experiment 2). Relative motion was altered both by moving the probe actively over a stationary surface (active mode) and by moving the surfaces under the stationary probe (passive mode). Substantial effects of speed were obtained relative to previous studies. The results are examined both in terms of the complex effects of speed on the psychophysical roughness functions and in terms of an increase in the size of the maximum speed effect as the range of speeds explored was reduced. We also consider how best to minimize potentially negative effects of speed on the haptic exploration of simulated textures. Two operator training procedures are proposed to achieve effective haptic exploration strategies.

Klatzky, R.L. & **Lederman, S.J.** (1999). ***Tactile roughness perception with a rigid link interposed between skin and surface.*** Perception & Psychophysics, 61(4), 591-607

Abstract

Subjects made roughness judgments of textured surfaces made of raised elements, while holding stick-like probes or through a rigid sheath mounted on the fingertip. These rigid links, which impose vibratory coding of roughness, were compared with the finger (bare or covered with a compliant glove), using magnitude-estimation and roughness differentiation tasks. All end effectors led to an increasing function relating subjective roughness magnitude to surface interelement spacing, and all produced above-chance roughness discrimination. Although discrimination was best with the finger, rigid links produced greater perceived roughness for the smoothest stimuli. A peak in the magnitude-estimation functions for the small probe and a transition from calling more sparsely spaced surfaces rougher to calling them smoother were predictable from the size of the contact area. The results indicate the potential viability of vibratory coding of roughness through a rigid link and have implications for teleoperation and virtual-reality systems.

Klatzky, R.L., **Lederman, S.J.** & Mankinen, J.M. (2005). ***Visual and haptic exploratory procedures in children's judgments about tool function.*** Infant Behavior & Development, 28, 240-249.

Abstract
Preschool children (M age = 4 years, 7 months) verbally judged whether a spoon would function to transport a target object (small versus large candy) and whether a stick would function to stir a target substance (sugar versus gravel). The spoons varied in bowl size, and sticks varied in rigidity. Children's judgments were sensitive to task goals (transport versus mixing), to tool properties (size and rigidity), and to target properties (size to be transported; resistance to mixing). Moreover, children used appropriate perceptual exploration to determine tool function. Judgments about transport were made after visual inspection of the spoon, and judgments about rigidity were made after haptic exploration of the stick. Children did not directly perform the task in order to judge whether the tool would be adequate. Differential visual and haptic object exploration during a perceptual-comparison task additionally confirmed the role of perceptual exploration in determining tool function.

Jones, L.A. & Lederman, S.J. (2006). Human Hand Function, New York: Oxford University Press.

Human Hand Function is a multidisciplinary book that reviews the sensory and motor aspects of normal hand function from both neurophysiological and behavioral perspectives. Jones and Lederman present hand function as a continuum ranging from activities that are essentially sensory in nature to those that have a strong motor component. They delineate four categories of function along this sensorimotor continuum: tactile sensing, active haptic sensing, prehension, and non-prehensile skilled movements. The authors then use these four categories as a framework for analyzing and synthesizing the results from a broad range of studies that has contributed to our understanding of how the normal human hand functions.

Human Hand Function begins with a historical overview of research on the hand and a discussion of the evolutionary development of the hand in terms of anatomical structure. In subsequent chapters the authors review the research in each of the four categories along the continuum. Jones and Lederman cover topics such as the intensive spatial, temporal, and thermal sensitivity of the hand, the role of hand movements in recognizing common objects, the control of reaching and grasping movements, and the organization of keyboard skills. The authors also examine how sensory and motor function develops in the hand from birth to old age, and how the nature of the end effector (e.g., a single finger or the whole hand) that is used to interact with the environment influences the types of information obtained and the tasks performed. The book closes with an assessment of how basic research on the hand has contributed to an array of more applied domains, including communication systems for the blind, haptic interfaces used in teleoperation and virtual-environment applications, tests used to assess hand impairments, and haptic exploration in art. *Human Hand Function* will be a valuable resource for students and professional researchers in neuroscience, cognitive psychology, engineering, human-technology interaction, and physiology.

Kitada, R., Johnsrude, I., Kochiyama, T. & **Lederman, S.J** (2010). ***Brain networks involved in haptic and visual identification of facial expressions of emotion: An fMRI study.*** Neuroimage, 49(2), 1677-1689.

Abstract
Previous neurophysiological and neuroimaging studies have shown that a cortical network involving the inferior frontal gyrus (IFG), inferior parietal lobe (IPL) and cortical areas in and around the posterior superior temporal sulcus (pSTS) region is employed in action understanding by vision and audition. However, the brain regions that are involved in action understanding by touch are unknown. Lederman et al. (2007) recently demonstrated that humans can haptically recognize facial expressions of emotion (FEE) surprisingly well. Here, we report a functional magnetic resonance imaging (fMRI) study in which we test the hypothesis that the IFG, IPL and pSTS regions are involved in haptic, as well as visual, FEE identification. Twenty subjects haptically or visually identified facemasks with three different FEEs (disgust, neutral and happiness) and casts of shoes (shoes) of three different types. The left posterior middle temporal gyrus, IPL, IFG and bilateral precentral gyrus were activated by FEE identification relative to that of shoes, regardless of sensory modality. By contrast, an inferomedial part of the left superior parietal lobule was activated by haptic, but not visual, FEE identification. Other brain regions, including the lingual gyrus and superior frontal gyrus, were activated by visual identification of FEEs, relative to haptic identification of FEEs. These results suggest that haptic and visual FEE identification rely on distinct but overlapping neural substrates including the IFG, IPL and pSTS region.

Lederman, S.J., Kitada, R., & Klatzky, R.L. (2010). ***Haptic Face Processing and its Relation to Vision.*** In M.J. Naumer & J. Kaiser (eds). Multisensory Object Perception in the Primate Brain. Springer Verlag, Ch 15, pp. 273-300

Abstract
In this chapter, we address the nature of haptic face perception. People can perform this task well above chance with relatively little training. We concentrate on how the haptic system processes and represents facial identity and emotional expressions both functionally and neurally. With respect to face processes, we consider issues that pertain to configural versus feature-based processing, to visual-mediation versus multisensory processing, and to intersensory transfer. With respect to face representations, we consider the role of orientation, the relative importance of different facial regions to haptic face perception, and the theoretical approaches that have been applied to the study of human facial emotions. Additionally, we address what is known about the corresponding neural mechanisms that subserve haptic face perception. We also relate this relatively new sub-area of haptic perception to the more extensive literature on visual face processing.

Kitada, R., Johnsrude, I., Kochiyama, T. & **Lederman, S.J.** (2009). ***Functional specialization and convergence in the occipitotemporal cortex supporting haptic and visual identification of human faces and body parts: An fMRI study.*** Journal of Cognitive Neuroscience, 21(10), 2027-2045

Abstract
Humans can recognize common objects by touch extremely well whenever vision is unavailable. Despite its importance to a thorough understanding of human object recognition, the neuroscientific study of this topic has been relatively neglected. To date, the few published studies have addressed the haptic recognition of nonbiological objects. We now focus on haptic recognition of the human body, a particularly salient object

category for touch. Neuroimaging studies demonstrate that regions of the occipito-temporal cortex are specialized for visual perception of faces (fusiform face area, FFA) and other body parts (extrastriate body area, EBA). Are the same category-sensitive regions activated when these components of the body are recognized haptically? Here, we use fMRI to compare brain organization for haptic and visual recognition of human body parts. Sixteen subjects identified exemplars of faces, hands, feet, and nonbiological control objects using vision and haptics separately. We identified two discrete regions within the fusiform gyrus (FFA and the haptic face region) that were each sensitive to both haptically and visually presented faces; however, these two regions differed significantly in their response patterns. Similarly, two regions within the lateral occipito-temporal area (EBA and the haptic body region) were each sensitive to body parts in both modalities, although the response patterns differed. Thus, although the fusiform gyrus and the lateral occipito-temporal cortex appear to exhibitmodality-independent, category-sensitive activity, our results also indicate a degree of functional specialization related to sensory modality within these structures.

Lederman, S.J., Klatzky, R.L., Rennert-May, E., Lee, J.H., Ng, K., & Hamilton, C. (2008). ***Haptic processing of facial expressions of emotion in 2D raised-line drawings.*** IEEE Transactions on Haptics, 1(1), 27-38

Abstract

Participants haptically (versus visually) classified universal facial expressions of emotion (FEEs) depicted in simple 2D raised-line displays. Experiments 1 and 2 established that haptic classification was well above chance; face-inversion effects further indicated that the upright orientation was privileged. Experiment 2 added a third condition in which the normal configuration of the upright features was spatially scrambled. Results confirmed that configural processing played a critical role, since upright FEEs were classified more accurately and confidently than either scrambled or inverted FEEs, which did not differ. Because accuracy in both scrambled and inverted conditions was above chance, feature processing also played a role, as confirmed by commonalities across confusions for upright, inverted, and scrambled faces. Experiment 3 required participants to visually and haptically assign emotional valence (positive/negative) and magnitude to upright and inverted 2D FEE displays. While emotional magnitude could be assigned using either modality, haptic presentation led to more variable valence judgments. We also documented a new face-inversion effect for emotional valence visually, but not haptically. These results suggest that emotions can be interpreted from 2D displays presented haptically as well as visually; however, emotional impact is judged more reliably by vision than by touch. Potential applications of this work are also considered.

Lederman, S.J., Klatzky, R.L., Abramowicz, A., Salsman, K., Kitada, R., & Hamilton, C. (2007). ***Haptic recognition of static and dynamic expressions of emotion in the live face.*** Psychological Science, 18(2), 158-164.

Abstract

If humans can detect the wealth of tactile and haptic information potentially available in live facial expressions of emotion (FEEs), they should be capable of haptically recognizing the six universal expressions of emotion (anger, disgust, fear, happiness, sadness, and surprise) at levels well above chance.We tested this hypothesis in the experiments reported here. With minimal training, subjects' overall mean accuracy was 51% for static FEEs (Experiment 1) and 74% for dynamic FEEs (Experiment 2). All FEEs except static fear were successfully recognized above the chance level of 16.7%. Complementing these findings, overall confidence and information transmission were higher for dynamic than for corresponding static faces. Our performance measures (accuracy and confidence ratings, plus response latency in Experiment 2 only) confirmed that happiness, sadness, and surprise were all highly recognizable, and anger, disgust, and fear less so.

Lederman, S.J., Kilgour, A., Kitada, R., Klatzky, R.L. & Hamilton, C. (2007). ***Haptic face processing.*** Canadian Journal of Experimental Psychology, 61(3), 230-241.

Abstract
We present an overview of a new multidisciplinary research program that focuses on haptic processing of human facial identity and facial expressions of emotion. A series of perceptual and neuroscience experiments with live faces and/or rigid three-dimensional facemasks is outlined. To date, several converging methodologies have been adopted: behavioural experimental studies with neurologically intact participants, neuropsychological behavioural research with prosopagnosic individuals, and neuroimaging studies using fMRI techniques. In each case, we have asked what would happen if the hands were substituted for the eyes. We confirm that humans can haptically determine both identity and facial expressions of emotion in facial displays at levels well above chance. Clearly, face processing is a bimodal phenomenon. The processes and representationsthat underlie such patterns of behaviour are also considered.

Kilgour, A.R., de Gelder, B., & **Lederman, S.J.** (2004). ***Haptic face recognition and prosopagnosia.*** Neuropsychologia, 42, 707-712.

Abstract

Cases of cross-modal influence have been observed since the beginning of psychological science. Yet some abilities like face recognition are traditionally only investigated in the visual domain. People with normal visual face-recognition capacities identify inverted faces more poorly than upright faces. An abnormal pattern of performance with inverted faces by prosopagnosic individuals is characteristically interpreted as evidence for a deficit in configural processing essential for normal face recognition. We investigated whether such problems are unique to vision by examining face processing by hand in a prosopagnosic individual. We used the haptic equivalent of the visual-inversion paradigm to investigate haptic face recognition. If face processing is specific to vision, our participant should not show difficulty processing faces haptically and should perform with the same ease as normal controls. Instead, we show that a prosopagnosic individual cannot haptically recognize faces. Moreover, he shows similar abnormal inversion effects by hand and eye. These results suggest that face-processing deficits can be found across different input modalities. Our findings also extend the notion of configural processing to haptic face and object recognition.

Kilgour, A., Servos, P., James, T. & **Lederman, S.J.** (2004). ***Haptic face recognition: an fMRI study.*** Brain and Cognition, 54(2), 159-161.

Abstract
We used functional MRI to investigate haptic face recognition and to investigate whether neural pathways dedicated to visual face recognition are also activated when participants explored clay facemasks haptically. Participants were trained to recognize masks of human faces and clay nonsense objects by touch only. During scanning, trained participants were required to identify the facemasks by name and the nonsense objects (nonface controls) by letter. Haptic face recognition produced activation within several extrastriate areas known to be involved in visual face recognition tasks. The results indicate that haptic and visual face recognition activates similar pathways, suggesting that face recognition is a multisensory phenomenon.

Kilgour, A.R., & **Lederman, S.J.** (2002). ***Face recognition by hand.*** Perception & Psychophysics, 64(3) , 339-352.

Abstract
We investigated participants' ability to identify and represent faces by hand. In Experiment 1, participants proved surprisingly capable of identifying unfamiliar live human faces using only their sense of touch. To evaluate the contribution of geometric and material information more directly, we biased participants toward encoding faces more in terms of geometric than material properties, by varying the exploration condition. When participants explored the faces both visually and tactually, identification accuracy did not improve relative to touch alone. When participants explored masks of the faces, thereby eliminating material cues, matching accuracy declined substantially relative to tactual identification of live faces. In Experiment 2, we explored intersensory transfer of face information between vision and touch. The findings are discussed in terms of their relevance to haptic object processing and to the face-processing literature in general.

Kitada, R., Hashimoto, T., Kochiyama, T, Kito, T, Okada, T., Matsumura, M., **Lederman, S.J.,** & Sadato, N. (2005). ***Graded response in the human brain for tactile roughness estimation of gratings: An fMRI study.*** NeuroImage , 25 , 90-100.

Abstract

Human subjects can tactually estimate the magnitude of surface roughness. Although many psychophysical and neurophysiological experiments have elucidated the peripheral neural mechanisms that underlie tactile roughness estimation, the associated cortical mechanisms are not well understood. To identify the brain regions responsible for the tactile estimation of surface roughness, we used functional magnetic resonance imaging (fMRI). We utilized a combination of categorical (subtraction) and parametric factorial approaches wherein roughness was varied during both the task and its control. Fourteen human subjects performed a tactile roughnessestimation task and received the identical tactile stimulation without estimation (noestimation task). The bilateral parietal operculum (PO), insula and right lateral prefrontal cortex showed roughness-related activation. The bilateral PO and insula showed activation during the noestimation task, and hence might represent the sensory-based processing during roughness estimation. By contrast, the right prefrontal cortex is more related to the cognitive processing, as there was activation during the estimation task compared with the no-estimation task, but little activation was observed during the no-estimation task in comparison with rest. The lateral prefrontal area might play an important cognitive role in tactile estimation of surface roughness, whereas the PO and insula might be involved in the sensory processing that is important for estimating surface roughness.

Newman, S.D., Klatzky, R.L., **Lederman, S.J.** & Just, M.A. (2004). ***Imagining material versus geometric properties of objects: an fMRI study.*** Cognitive Brain Research, 23(2-3), 235-246.

Abstract

Two experiments are reported that used fMRI to compare the brain activation during the imagery of material and geometric object features. In the first experiment, participants were to mentally evaluate objects along either a material dimension (roughness, hardness and temperature; e.g., Which is harder, a potato or a mushroom?) or a geometric dimension (size and shape; e.g., Which is larger, a pumpkin or a cucumber?). In the second experiment, when given the name of an object and either a material (roughness and hardness) or geometric (size and shape) property participants rated the object on a scale from 1 to 4. Both experiments were designed to examine the underlying neural substrate that supports the processing of material object properties with respect to geometric properties. Considering the relative amount of activation across the two types of object properties, we found that (1) the interrogation of geometric features differentially evokes visual imagery which involves the region in and around the intraparietal sulcus, (2) the interrogation of material features differentially evokes the processing of semantic object representations which involves the inferior extrastriate region, and (3) the lateral occipital cortex (LOC) responds to shape processing regardless of whether the feature being queried is a material or geometric feature.

See also **“Haptic Face Processing”**

Pawluk D., Kitada, R., Abramowicz A., Hamilton C., & **Lederman SJ.** (2010). ***Haptic figure-ground differentiation via a haptic glance.*** Proceedings of the Annual Haptics Symposium on Teleoperator and Virtual-Environment Systems, IEEE Haptics Symposium, 25-26 March, Waltham Massachusetts, USA, 63-66.

Abstract
This study begins to address the nature of human haptic perceptual organization by examining "figure/ground" segmentation from a haptic perspective (i.e., differentiating an object from its supporting surface). The experiment focuses on the perception of the presence of an object via brief contact (i.e., a haptic glance) when both kinetic properties and geometric properties are manipulated. The results suggest that contact with objects that are moveable (cf. fixed) and tall (cf. short) greatly increases the perceived probability that an object is present. The effect of kinetics is further heightened when moveable objects have convexly curved bases.

D. Pawluk, R. Kitada, A. Abramowicz, C. Hamilton, and **S. J. Lederman** (2010). ***Figure/Ground Segmentation via a Haptic Glance: Attributing Initial Finger Contacts to Objects or their Supporting Surfaces***, IEEE: Transaction on Haptics (preprint on IEEE Xplore)

Abstract
The current study addresses the well-known "figure/ground" problem in human perception, a fundamental topic that has received surprisingly little attention from touch scientists to date. Our approach is grounded in, and directly guided by, current knowledge concerning the nature of haptic processing. Given inherent figure/ground ambiguity in natural scenes and limited sensory inputs from first contact (a "haptic glance"), we consider first whether people are even capable of differentiating figure from ground (Experiments 1 and 2). Participants were required to estimate the strength of their subjective impression that they were feeling an object (i.e., figure) as opposed to just the supporting structure (i.e., ground). Second, we propose a tripartite factor-classification scheme to further assess the influence of kinetic, geometric (Experiments 1 and 2), and material (Experiment 2) factors on haptic figure/ground segmentation, complemented by more open-ended subjective responses obtained at the end of the experiment. Collectively the results indicate that under certain conditions it is possible to segment figure from ground via a single haptic glance with a reasonable degree of certainty, and that all three factor classes influence the estimated likelihood that brief, spatially distributed fingertip contacts represent contact with an object and/or its background supporting structure.

Kitada, R., Dijkerman, H. C., Soo, G. & **Lederman, S.J.** (2010). ***Representing human hands haptically or visually from first-person versus third-person perspectives.*** Perception, 39, 236-254.

Abstract
Humans can recognise human body parts haptically as well as visually. We employed a mental-rotation task to determine whether participants could adopt a third-person perspective when judging the laterality of life-like human hands. Female participants adopted either a first- person or a third-person perspective using vision (experiment 1) or haptics (experiment 2), with hands presented at various orientations within a horizontal plane. In the first-person perspective task, most participants responded more slowly as hand orientation increasingly deviated from the participant's upright orientation, regardless of modality. In the visual third-person perspective task, most participants responded more slowly as hand orientation increasingly deviated from the experimenter's upright orientation; in contrast, less than half of the participants produced this same inverted U-shaped response-time function haptically. In experiment 3, participants were explicitly instructed to adopt a third-person perspective haptically by mentally rotating the rubber hand to the experimenter's upright orientation. Most participants produced an inverted U-shaped function. Collectively, these results suggest that humans can accurately assume a third-person perspective when hands are explored haptically or visually.With less explicit instructions, however, the canonical orientation for hand representation may be more strongly influenced haptically than visually by body-based heuristics, and less easily modified by perspective instructions.

See also **“Haptic Face Processing”**

Purdy, K.A., **Lederman, S.J.** & Klatzky, R.L. (1999). ***Manipulation with partial or no vision.*** Journal of Experimental Psychology: Human Perception & Performance, 25(3),755-774.

Abstract

The present study investigated the role of vision in closed- and open-loop processing during manipulation. In Experiment 1, participants performed common manipulatory tasks with 100% accuracy in less than 1s without vision. In Experiment 2, the effects of extensive practice of a peg-in-hole task were examined within four functionally significant stages of manipulation. Performance was consistently faster with than without vision in the pre-reach, grasp, and transport + insert stages; reverse effects were observed during the reach stage. In Experiment 3, the effects of practice with partial vision were examined: participants initially learned the peg-inhole task with full vision, then transferred to learning the same task with vision only available during one functional stage. Overall, performance was fastest when vision was limited to the prereach and reach stages.

Lederman, S.J. & Wing, A.M. (2003). ***Perceptual Judgement, Grasp Point Selection and Object Symmetry.*** Experimental Brain Research, 152, 156-165.

Abstract
Object symmetry is a visual attribute that may contribute to perceptual judgement and to action. We evaluated the effects of varying the physical symmetry of planar objects (presence versus absence) on both aspects. In Experiment 1, subjects estimated the magnitude of visually perceived symmetry of the objects. The results confirmed the influence of physical symmetry on perceived symmetry, and supported our binary categorisation of stimulus objects in terms of presence versus absence of physical symmetry . In Experiment 2, participants used a precision grip to grasp and stably lift the same planar objects varying in degree of symmetry. Choice of grasp points was unrestricted. Participants selected a grasp axis (between thumb and middle finger) that limited the perpendicular distance from CM (i.e., grasp-axis error) to just a few millimetres. Moreover they took advantage of visual cues to object symmetry to better determine CM, thus reducing their grasp-axis error for symmetric (vs. asymmetric) objects by 31%. We interpret these findings in terms of user and object-geometry constraints on grasp-point selection.

Wing, A.M. & **Lederman, S.J**. (1998). ***Anticipating load torques produced by voluntary movements.*** Journal of Experimental Psychology: Human Perception & Performance, 24 (6), 1571-1581.

Abstract
The stability of an object held between the finger and thumb depends on friction developed by grip force, normal to the contact surfaces, to overcome tangential load force. Previous research has shown that in lifting an object, grip force rises with the increase in gravitational load force as the hand takes the weight and that in moving an object, grip force is adjusted to meet movement induced inertial load force. Those results demonstrated the anticipatory nature of coordination of grip force with load force. Whether grip force anticipates load torque was studied in this research. When participants were constrained to use grasp points where the grasp axis was manifestly distant from object center of mass, it was found that they made grip force adjustments in anticipation of load torques that tended to destabilize an object as a result of lifting or moving it. These adjustments imply use of information about object center of mass in movement planning.

Ellis, R.R., Flanagan, R. & **Lederman, S.J.** (1999). ***The influence of visual illusions on grasp position.*** Experimental Brain Research, 125 , 109-114.

Abstract
Visual size illusions have been shown to affect perceived object size but not the aperture of the hand when reaching to those same objects. Thus, vision for perception is said to be dissociated from vision for action. The present study examines the effect of visual-position and visual-shape illusions on both the visually perceived center of an object and the position of a grasp on that object when a balanced lift is required. The results for both experiments show that although the illusions influence both the perceived and grasped estimates of the center position, the grasp position is more veridical. This partial dissociation is discussed in terms of its implications for streams of visual processing.

Lawrence, M.A., Kitada, R., Klatzky, R.L. & **Lederman, S.J.** (2007). ***Haptic roughness perception of linear gratings via bare finger or rigid probe.*** Perception, 36, 547-557.

Abstract
The magnitude of perceived roughness was haptically estimated as subjects freely explored linear gratings with either the bare finger or a rigid stylus-shaped probe. A considerably expanded range of ridge and groove width was investigated, relative to the extant literature. The four experiments collectively indicate that, for both finger and probe-end effectors, the variance in the estimates of perceived roughness was predominantly predicted by a single parameter: groove width. The functions relating perceived roughness to groove width increased over a narrow band relative to the full range of values, then flattened. These data have archival values for models of roughness perception involving both direct and indirect touch.

Klatzky, R.L. & **Lederman, S.J.** (2006). ***The perceived roughness of resistive virtual textures: I. Rendering by a force-feedback mouse.*** ACM: Transactions of Applied Perception, 3 (1), 1-14.

Abstract
In previous work we demonstrated that people reliably perceive variations in surface roughness when textured surfaces are explored with a rigid link between the surface and the skin [e.g., Klatzky and Lederman, 1999; Klatzky et al. 2003]. Parallel experiments here investigated the potential of a force-feedback mouse to render surfaces varying in roughness. The stimuli were surfaces with alternating regions of high and low resistance to movement in the x dimension (called ridges and grooves, respectively). Experiment 1 showed that magnitude ratings of roughness varied systematically with the spatial period of the resistance variation. Experiments 2 and 3 used a factorial design to disentangle the contributions of ridge and groove width. The stimuli constituted eight values of groove width at each of five levels of ridge width (Experiment 2) or the reverse (Experiment 3). Roughness magnitude increased with ridge width while remaining essentially invariant over groove width. Kinematic variations in exploration were observed across the surfaces. The data point to the promise of using inexpensive devices to create virtual textural variations under conditions of unconstrained exploration.

Lederman, S.J., Klatzky, R.L., Tong, C. & Hamilton, C. (2006). ***The perceived roughness of resistive virtual textures: Effects of varying viscosity with a force-feedback device.*** ACM:Transactions of Applied Perception, 3 (1), 15-30.

Abstract
Klatzky and Lederman (2006) have shown that tangential resistive forces may be used to convey roughness of virtual textures using the Wingman force-feedback mouse. Modeling our experiment after that study, we directly examined the effect of viscous resistance on the perceived roughness magnitude of virtual gratings using a PHANTOM. For each virtual grating, the resistance level encountered at the ridges was varied by altering the viscosity coefficient. Perceived roughness increased with increasing viscosity coefficient. The ridge-to-groove ratio contributed a small additional effect. These results suggest that simple models of viscous resistance may be used to simulate varying levels of surface roughness.

Klatzky, R.L. & **Lederman, S.J.** (1999). ***Tactile roughness perception with a rigid link interposed between skin and surface.*** Perception & Psychophysics, 61(4), 591-607.

Abstract
Subjects made roughness judgments of textured surfaces made of raised elements, while holding stick-like probes or through a rigid sheath mounted on the fingertip. These rigid links, which impose vibratory coding of roughness, were compared with the finger (bare or covered with a compliant glove), using magnitude estimation and roughness differentiation tasks. All end effectors led to an increasing function relating subjective roughness magnitude to surface interelement spacing, and all produced above-chance roughness

discrimination. Although discrimination was best with the finger, rigid links produced greater perceived roughness for the smoothest stimuli. A peak in the magnitude-estimation functions for the small probe and a transition from calling more sparsely spaced surfaces rougher to calling them smoother were predictable from the size of the contact area. The results indicate the potential viability of vibratory coding of roughness through a rigid link and have implications for teleoperation and virtual-reality systems.

Lederman, S.J. & Klatzky, R.L. (1999). ***Sensing and displaying spatially distributed fingertip forces in haptic interfaces for teleoperator and virtual environment systems.*** Presence: Teleoperators and Virtual Environments, 8(1), 86-103.

Abstract
This article reports a variety of sensory and perceptual consequences of eliminating, via a rigid fingertip sheath, the spatially distributed fingertip force information that is normally available during tactile and haptic sensing. Sensory measures included tactile spatial acuity, tactile force, and vibrotactile thresholds. Suprathresholds tasks included perception of roughness, perception of 2-D edge orientation, and detection of a simulated 3-D mass in simulated tissue via fingertip palpation. Of these performance measures, only vibrotactile thresholds and texture perception failed to show substantial impairment. The results are discussed in terms of their implications for the future design of haptic interfaces for teleoperator and virtual environment systems.

Wagner, C.R., **Lederman, S.J.** & Howe, R.D. (2004). ***Design and performance of a tactile shape display using RC servomotors.*** Haptics-e (The Electronic Journal of Haptic Research), 3 (No. 4).

Abstract

Tactile displays are used to convey small-scale force and shape information to the fingertip. We describe a 6 x 6 tactile shape display design that is low in cost and easily constructed. It uses commercially available RC servomotors to actuate an array of mechanical pins. The pins deflect a maximum of 2 mm, with a resolution of 0.1 mm. The pin center spacing is 2 mm and the pin diameter is 1 mm. For the maximum deflection of 2 mm, the display can represent frequencies up to 7.5 Hz; smaller deflections lead to achievable frequencies up to 25 Hz because the servos are slew rate limited. This design is well suited to tactile display research, as it offers reasonable performance in a robust and inexpensive package.

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