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Measuring the Impossible

Report of a MINET High-Level Expert Group

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1. What is 'Measuring the Impossible'

'Measuring the Impossible' refers to new and innovative research activities related to the measurement of quantities and qualities that are dependent on *human perception and/or interpretation*. This includes, for example, perceived attributes of products and services, such as quality or desirability, and societal characteristics such as security or health. Measuring the Impossible (MtI) aims at consensus on how 'generic' metrological issues are currently applied or can be applied specifically to understanding, quantifying or predicting human perception and interpretation (i.e. 'Measurement of Persons'). Examples of 'generic' issues are (a) measurement concepts and terminology, (b) measurement techniques and instruments, (c) measurement uncertainty and reliability, and (d) decision making, impact assessment and validity.

A key aspect of research in this area is that it must be of an interdisciplinary nature, involving, for example, investigations of human mental and brain[1] functions (studied primarily in psychology and neuroscience), research into how these underpin human attention, perception and cognition (psychophysics and behavioural studies) and development of measurement instrumentation and perceptual models (metrology, mathematics, modelling, computing, psychology, physics, and psychophysics). Furthermore, 'Measurement of Persons' has two meanings, on the one hand, 'Measuring various characteristics of the Person(s)'; on the other hand 'Person(s) used as a Measuring Instrument'. In the first meaning, the measurand relates to a person or population but may be physical (e.g., body weight),[2] physiological (e.g., heart rate), psychological (e.g., personality[3]), social (e.g., sociability), or philosophical (e.g., capacity for original thought) in nature. In the second meaning the measurand originates in human perception and/or interpretation, but is typically 'attributed' to an external object or environment (e.g., quality or comfort of products), the society (e.g., information systems, cooperative climate, interactive behaviour), other persons (e.g., movement, behaviour, communication) or the person themselves (e.g., emotions, logics, symptoms). One important category of 'Person(s) as a measuring instrument' is the practice of self-reporting, in which Person by necessity constitutes part of the 'measuring instrument' for measuring their own characteristics, e.g., emotions, personality, chronic pain condition[4] or mental depression.[5]

Human perception and/or interpretation encompasses phenomena that are of different complexity, ranging from sensory perceptions (e.g. colour, taste, odour, loudness), to environmental perceptions (e.g., soundscape, air quality, landscape), to self-perceptions (e.g., chronic pain, wellbeing, mood), to perceptual attributions (e.g., aesthetics, satisfaction, expectancies), as well as all kinds of complex interpretations and evaluations (e.g., utility, risk, maladjustment) that are based on learning and experience. Notably, there are no limits in time for the measurement of 'Person(s); it may embrace the past, the present and the future, as well as interconnecting these.

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[1] Blackmore, S. *Conversations on Consciousness. What the Best Minds Think about the Brain, Free Will and What it Means to be Human.* Oxford: Oxford University Press, 2006.

[2] The International Commission on Radiological Protection (W.S. Snyder, chair). *Report of the Task Group on Reference Man.* ICRP Publication 23. New York: Pergamon Press, 1975.

[3] Lord, F.M., & Novick, M.R. *Statistical Theories of Mental Test Scores.* Reading, Mass., Addison Wesley Pub., 1968.

[4] Melzack, R. The McGill Pain Questionnaire: Major properties and scoring methods. *Pain*, 1, 277-299.

[5] Beck, A.T., Steer, R.A., & Garbin, M.G. Psychometric properties of the Beck Depression Inventory: Twenty-five years of evaluation. *Clinical Psychology Review*, 1988, 8, 77-100.

The interdisciplinary nature of MtI research raises many challenges. In many disparate disciplines/interdisciplines, related but so far unconnected developments have to be investigated and interlinked. For example, valid decision-making requires improved measurement based on human perception and/or human interpretation of qualitative information. As proposals for future projects in the MtI field are put forward, it is essential that mechanisms are in place to facilitate interdisciplinary science communication and creativity, not only among researchers, but also in the evolving wider European community.

1.1 Measurement Systems and Processes

A 'process' can be defined as a system that generates information.[6] Examples of information variables that are generated by physical and chemical processes are: (a) a moving car generates displacement, velocity and acceleration variables and (b) a chemical reactor generates temperature, pressure and composition variables. Similarly, a person can be considered to generate a number of information variables through perceptual, cognitive and emotional processes. Thus, sensory perception can be described as a process that generates information variables, such as environmental perceptions (e.g., odours from a pulp mill). Alternatively, sensory perception may also be described as a measurement system that typically consists of several elements or blocks: a sensing element (e.g. olfactory receptors in the nose), a signal-conditioning element (e.g. the olfactory bulb), a signal-processing element (e.g. the olfactory cortex in the brain) and finally a data-presentation element (brain-mind 'bridging' of neurobiochemical activity and the mental awareness of odours; the perception). The measurement system may also include between-element feedback loops and brain-mind interactive communication processes.[7] Understanding these types of measurement systems and processes lies at the centre of the 'Measuring the Impossible' initiative.

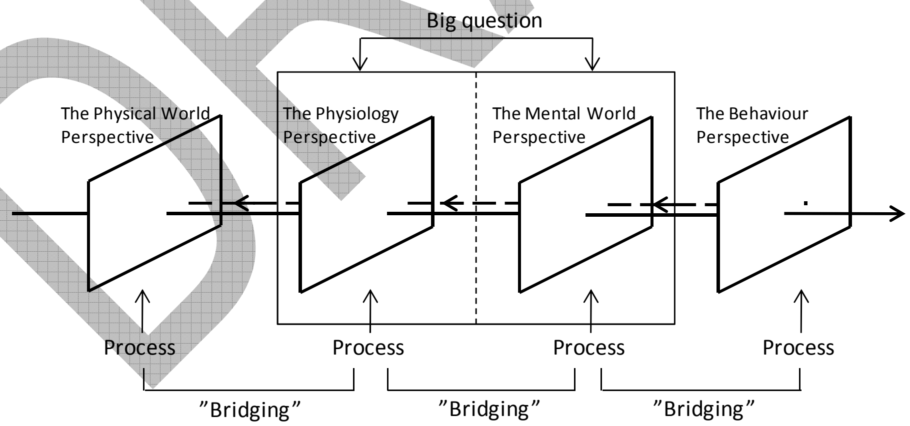

Figure 1. Theoretical representation of the processes, interconnections and measurement systems that are involved in the 'Measuring the Impossible' area.

6 Bentley, J.P. *Principles of Measurement Systems*. Harlow, UK: Pearson Education Ltd., 2005 (4th ed.).

7 Popper, K.R., & Eccles, J.C. *The Self and Its Brain. An Argument for Interactionism*. Berlin: Springer International, 1981.

Figure 1 illustrates the various interconnections between monodisciplinary research areas and associated measurement systems and processes that are of relevance for Measuring the Impossible. Each of the planes represents the areas of physics, physiology, mental part of psychology, and (overt) behavioural sciences. In each of these four science areas there are phenomena and theories as well as processes and methods, which are applied and/or practiced in monodisciplinary research. Some of the processes are utilized in measurement systems. The square embracing the physiology and mental boxes represents processes 'inside' human being(s) and the dotted vertical line represents the brain-mind 'bridging'; understanding this relationship is one of the 'big questions' in Measuring the Impossible. The behaviour box here refers to overt behaviour, which is observed by other persons (e.g., a smiling face in snapshots or the reaction time in pressing a button).

Process-oriented research to measure behaviour or characteristics of individuals or groups of persons has primarily taken place within the individual disciplines shown in Figure 1, i.e., in physical, physiological, (mental) psychological, or (overt) behavioural sciences. Thus far, the main focus for interdisciplinary research has been on understanding the ways in which individual processes link together ('bridging' problems) using sensory physical, psychophysical and/or psychophysiological approaches. There are numerous examples in the field of 'sensory physics' that are based on the use of psychophysical methods, for example, (a) understanding the relationship between the physical properties of materials and human sensory perceptions such as tactile, olfactory or pain sensations and (b) understanding how the physical attributes of an environment are linked to mental features and processes such as decision making through the study of overt behaviour Increasingly these psychophysical experiments are being supplemented with psychophysiological methods, such as the use of neurobiological and neuroimaging techniques to measure human brain functions in order to understand better the (mental) perceptual or cognitive processes.

Figure 1 also depicts the different aspects of inner and outer psychophysics, both of which have important contributions to make to the field of MtI. In inner psychophysics, the process starts from physical properties and has mental properties (perception, cognition, emotion etc.) as the output result. In outer psychophysics, the process also starts from physics but instead has behaviour as the output result. In outer psychophysics, the process once again starts from the physical properties but in this case has behaviour as the output result. Outer psychophysics thereby handles physiology and mental processing as a combined 'black box' within which no measurement is performed. A key question to be addressed within MtI, as illustrated in Figure 1, is how to reveal the processes taking place within this 'black box', i.e. how to measure the two-way 'bridging' processes involved between the physiological processes and the mental processes and their outcomes, and to understand how perception, cognition, learning, memory and emotions build bridges between them. This issue has previously been overlooked in psychophysics but is of utmost importance for developing new kinds of measurement procedures and instruments with capacities far beyond current methods and devices. These will make it possible, for example, to measure how environmental conditions (soundscape, lighting quality, etc.) impact on feelings of comfort and wellbeing and thus to measure and model how these can be changed for maximum beneficial effect.

In order to clarify Figure 1, take an example of a person feeling pain from touching a hot pot. Electrical energy is used to heat the plates of a stove, which in turns heats the pot. The electrical power consumed and the temperature of the pot can be measured using traditional physics; we

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are in the *physics box*. If the person touches the pot, the warmth, touch and pain receptors in the hand are stimulated and induce a biochemical process involving a two-way transmission of signals via nerve cells to and from the brain, which thus starts ‘communicating’; we are in the *physiology box*. The signals are processed in the brain, leading to an awareness that the heat-pain being experienced (perceptually and emotionally) is because the hand is in contact with something hot; we are in the *mental box.* Finally, this ‘conclusion’ causes the brain to send new signals to relevant motor units of the muscles to remove the hand from the pot (immediate reflex); we are in the *behaviour box.* In terms of the ‘bridging’ processes shown in Figure 1, at least two need to be considered: one is bottom-up (from physiology of the receptors in the hand to the mental experience of heat-pain) and the other is top-down (from mental awareness of the cause of the heat-pain to the physiology of the motor units in the muscles of the hand). Using this resulting neural activity (both peripherally and in the brain) makes mental awareness happen, and how can this awareness generate an appropriate behavioural response?

Consider another example: that of choosing the desired colour of the bodywork when purchasing a new car. The spectral reflectance of samples of the various paint finishes available can be measured using traditional physics; we are in the *physics box*. When a person views the samples, the light reflected from the surface of the samples stimulates photoreceptors in the retina and induces a biochemical process involving transmission of signals via nerve cells and the optic nerve to the brain; we are in the *physiology box.* The brain processes these signals, leading to a perceptual awareness of the colour of the sample (red, green etc.) and an emotionally based decision on whether or not that is the colour that we wish the car to be painted; we are in the *mental box.* Finally, this decision causes the brain to send signals to relevant motor units of the vocal system to say ‘yes’ or ‘no’ for each available colour; we are in the *behaviour box.* Once again several ‘bridging’ processes are involved, both bottom-up and top-down, and the key issue for MtI lies in measuring and understanding these.

2. Current State-of-the-Art in the Context of MtI

Although a range of experimental methods, data analysis techniques, and models and methods of perceptual measurement have been developed during the past 150 years or so, there has been relatively little coordinated research aimed at developing a comprehensive understanding of human perception and interpretation. Figure 2 shows the multidisciplinary approaches that provide the links between the four main research areas of the MtI system presented in Figure 1, and that form the cornerstones for future advances in the MtI field. For example, neuroscience provides a way of studying the complex link between the Physiology and Mental World perspectives. This section gives a brief summary of the key developments and current state-of-the-art in these various research disciplines and interdisciplines.

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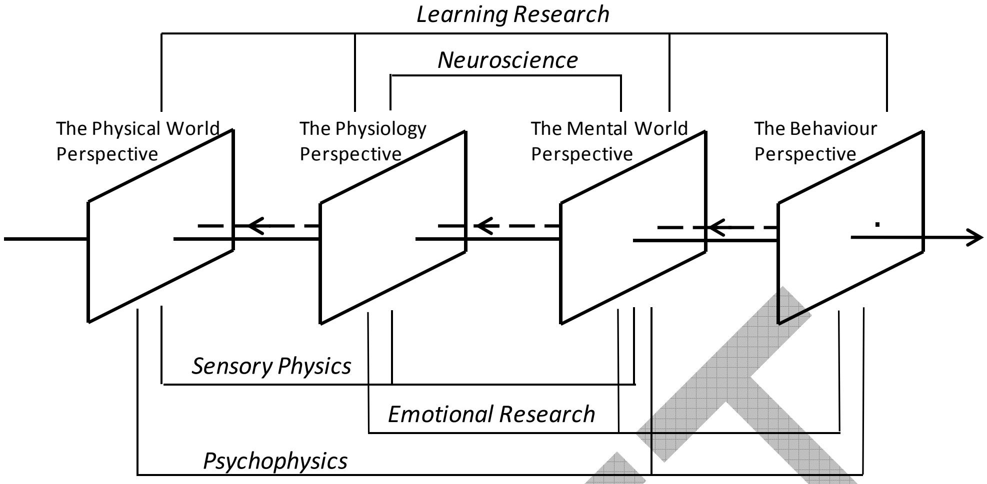

Figure 2. Schematic illustration of the multidisciplinary approaches that provide links between theoretical representation of the processes, interconnections and measurement systems involved in the 'Measuring the Impossible' area

2.1 The Physical World Perspective

A well-established measurement infrastructure is in place to support trade, industry, science, research and development throughout the world. It is based on calibrated measurement instrumentation, with demonstrable **traceability** to internationally agreed measurement scales and units, preferably SI units (Systéme International d´Unités). At the heart of this system is a network of National Measurement Institutes (NMIs), whose responsibility is to realise, maintain and disseminate reference measurement scales on a national or regional basis and to compare their own scales with those of other NMIs in order to ensure international compatibility of measurements.

The measurements carried out under the SI system are generally 'property-centred' i.e. the focus is on generating robust and objective measures, grounded in appropriate definition of the physical (or chemical) quantity to be measured (e.g. temperature, length, mass, reflectance, hardness, chemical composition). Whereas these measurements are robust, they were not designed with the human sensory system in mind. Rather, they are intended for fairly large samples with uniform bulk characteristics. Thus, they do not always relate well to the 'feature-centred' measurements associated with perceptual processes, either due to limitations in the sensitivity of existing instrumentation and standards (e.g., although systems for force measurements are well-established, these do not currently have the sensitivity necessary to measure the dynamic friction coefficient between, say, human skin and a flower petal) or because the physical quantities being measured are of a different nature to the perceptual quantities (e.g. instrumentation for measuring the optical characteristics of a material can be used to quantify the reflectance as a function of wavelength or position on the surface, but cannot provide results that relate directly to human perceptual qualities such as 'woody appearance'). Nevertheless these strictly physical or chemical measures are important and form the basis for reliable, reproducible and traceable measurements in all areas of science, including measurements used in other science areas for

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MtI, such as human physiological quantities (heart rate, brain activity, stress hormones or allergic reactions ,etc.) and brain imaging (fMRI, etc.).[8]

Key terms used in physical measurement	
Calibration	operation that, under specified conditions, establishes a relation for obtaining a measurement result from an indication on a measuring instrument
Measurement standard	realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference
International measurement standard	measurement standard recognized by signatories to an international agreement and intended to serve worldwide
Primary standard	measurement standard established using a primary reference measurement procedure, or an accepted physical artifact chosen by convention (e.g. international prototype of the kilogram)
Secondary standard	measurement standard established through calibration with respect to a primary measurement standard for a quantity of the same kind
Traceability	property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations; each step in the chain will contribute to the final measurement uncertainty
Traceability chain	sequence of measurement standards and calibrations that is used to relate a measurement result to a reference
Measurement error	measured value minus a reference value
Uncertainty	a parameter, associated with the result of a measurement, that characterises the dispersion of the values that could be reasonably attributed to the measurand
Standard measurement uncertainty	measurement uncertainty expressed as a standard deviation
Combined standard measurement uncertainty	standard measurement uncertainty obtained by combining the individual standard measurement uncertainties associated with each input quantity that may affect the measurement result
Type A evaluation of measurement uncertainty	evaluation of a component of measurement uncertainty by a statistical analysis of measured quantity values obtained under defined measurement conditions
Type B evaluation of measurement uncertainty	evaluation of a component of measurement uncertainty determined by means other than a Type A evaluation e.g. obtained from a calibration certificate, or from the accuracy class of a measuring instrument, or from limits deduced through experience
Accuracy	closeness of agreement between the measured value and the true value. As the true value is generally not known, accuracy is a qualitative term only and cannot be given a numerical value. A measurement is said to be more accurate when it offers a smaller measurement error.
Precision	closeness of agreement between measured values obtained by replicate measurements on the same or similar objects under specified conditions
Resolution (of a measuring instrument)	smallest change in a quantity being measured that causes a perceptible change in the corresponding indication (on the measuring instrument)
Repeatability	measure of the spread in results under conditions where independent results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time; usually quantified in terms of the standard deviation of the measurement results
Reproducibility	measure of the closeness of the agreement between the results of measurements of the same property on identical test items, when carried out under changed conditions of measurement (e.g. by a different operator or using a different method, or at a different time); usually quantified in terms of the standard deviation of the mean result obtained from each of the independent sets of measurements
Validity (of a measurement result)	availability of objective evidence that a given measurement result fulfils specified requirements, where the specified requirements are adequate for an intended use
Reliability (of a measurement result)	qualitative term expressing the degree of confidence that can be placed on a given measurement result

[8] Please note that some of these key terms of physical measurement are defined differently in the social sciences.

Physics also plays an important role in the measurement of quantities and qualities in the development of calibration of instrumentation that is used to measure the human physiological responses. Research is underway both to improve existing instrumentation and to develop new techniques, in order to meet the need, for example, for brain imaging with higher spatial and temporal resolution.

In recent years, there has been increasing interest in establishing measurement systems and instrumentation for the 'human sensing' or *sensory physics* approach. This focuses on trying to develop instruments or measurement metrics that in some way 'mimic' the performance of the human sensory systems. Such measurements are important because they have the potential to provide data that are directly related to the capabilities of the human sensory systems and are therefore able to contribute (however indirectly) to the creation of certain perceptions (or cognitions). This approach to measurement is relatively well advanced in the visual science community,[9] where systems that provide a robust method for quantifying the perceived colour and 'brightness' of various types of artefact (coloured materials, lamps, visual displays, etc.) have been successfully used throughout the world for many decades. These measurement systems have been developed through the use of psychophysical methods, in which an observer's perception is studied by systematically varying the properties of a stimulus along one or more physical dimensions. For example, the internationally agreed scale for measuring the luminous intensity of a light source was developed from the results of psychophysical experiments such as the ability to perceive flicker when two lights of slightly different colour and power are presented alternately at a high frequency.

Psychophysical methods have also been successful in the area of auditory perception where, for example, research on auditory masking phenomena (i.e. reduced audibility of a sound signal when in the presence of a second signal of higher intensity and within the same critical band) has led to new methods for measuring loudness of complex sounds[10] and more recent developments in the measurement of 'soundscape' (a sound or combination of sounds that forms or arises from an immersive environment) and auralisation (creating future soundscapes to supplement city plans) are currently being investigated for potential standardisation.[11]

Another important area of sensory physics, particularly considering that the skin is a vital part of the largest sensory system of the human body, is the development of systems to relate physical measurements to tactile perception. One subject of active research is the measurement of the surface structure of materials and the role of human fingerprints[12] in generating a resultant perception of roughness. Other research has focused on standardised methods of measurement for perceptual attributes such as softness, which is closely related to the physical property of compressibility. In comparison with vision science, the understanding of how basic mechanisms relate to human perception is at an early stage for the skin senses, in particular in respect of the multidimensional measurement that characterises haptic perception.[13] Nevertheless measurement

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9 Palmer, S.E. *Vision Science. Photons to Phenomenology*. Cambridge, Mass.: The MIT Press, 1999.

10 ISO 532-1975 (E). Acoustics–Method for calculating loudness level. International Organization for Standardization, Geneva, Switzerland.

11 ISO/TC 43/SC 1/WG54. Perceptual assessment of soundscape quality.. International Organization for Standardization, Geneva, Switzerland.

12 Wu, J.Z., Dong, R.G., Rakheja, S., Schopper, A.W., & Smutz, W.P. A structural fingertip model for simulating of the biomechanics of tactile sensation. *Medical Engineering & Physics*, 2004, 26, 165-175.

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

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has facilitated major advances in the areas of robotics[14] and textiles or paper[15] and research is now underway into relevant measurements for more complex perceptual attributes, such as visual *and* tactile texture or haptic perception integrating movements with the sensing of all the skin senses.

Development of measurement instrumentation is still at a rather embryonic stage – for taste and olfaction, despite the fact that in these areas the use of sensory techniques based on expert evaluation by human observers[16] is well entrenched in quality control, product development and research. Applications[17] involve the characterization and evaluation of foods and beverages, environmental odours, personal hygiene products, diagnosis of illnesses, testing of pure chemicals, designing perfumes, etc. Although the sense of taste itself is well understood, the evaluation of foods is multisensory and additionally involves perception of warmth, cold, texture, mild pain, etc. Olfaction is highly dependent on the chemical composition of the natural materials, gases and vapours in question, but in ways that are both complex and poorly understood. In spite of expansive developments and serious attempts at developing new instrumentation, so called 'electronic noses,[18] the problem of measuring the perceived 'odours' rather than just the constituent chemical components has as yet not been solved. Part of the problem is that compared to chemical instruments, even the human olfactory system detects odour of chemical compounds at very low concentrations.

2.2 The Physiology Perspective

Attempts to understand the structure and function of the various anatomical features of the human body date back to the time of Hippocrates, but it was not until the 19th century that details such as the structure of cells and nerve fibres became known. Since then, considerable advances have been made in our understanding of the physiology of the human sensory systems, such as the properties of the sensory receptors, the functioning of the human nervous system, and the areas of the brain that are activated when particular sensory receptors are stimulated. We understand, for example, the detailed structure of the retina (seeing), the functioning of the mechanoreceptors in our skin (touching), the ways in which electrical signals pass from tactile receptors in our fingertips along nerve fibres in the spinal column to the brain, and even how to implant mechanical structures into the ear (cochlear implants) which can restore hearing to persons, who have acquired deafness or hearing-impairment. These send electrical impulses from a miniature microphone to the nerves in the scala tympani and then directly to the brain through the auditory nerve system. However, our knowledge on how sensory signals are processed in the brain is still at a rudimentary stage, and this is where much current research activity is focused.

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14 Howe, R.D., & Cutkosky, R.M. Dynamic tactile sensing: perception of fine surface features with stress rate sensing. *IEEE Transactions on Robotics and Automation*, 1993, 9(2), 140.

15 Hollmark, H., & Ampulski, R.S. Measurement of tissue paper softness: A literature review. *Nordic Pulp and Paper Research Journal*, 2004, 19(3), 345-353.

16 Meilgaard, M., Civille, G.V., & Carr, B. T. *Sensory Evaluation Techniques*. Boston, Mass.: CRC Press Inc., 1991.

17 Meiselman, H.L., & Rivlin, R.S. (Eds.), *Clinical Measurement of Taste and Smell*. New York: Macmillan Pub. Co., 1986.

18 Pearce, T.C., Schiffman, S.S., Nagle, H.T., & Gardner, J.W. (Eds.). Handbook of machine olfaction. Weinheim: Wiley-VCH, 2002.

Brain Activity and Imaging Techniques

EP	Evoked Potentials
ERP	Event-Related Potential – an electrophysiological response to an internal or external stimulus
EEG	Electroencephalography
EMG	Electromyography
fMRI	functional Magnetic Resonance Imaging
fNIR	Functional Near-InfraRed Imaging
MEG	Magnetoencephalography
MIT	magnetic Induction Tomography
PET	Positron Emission Tomography
TMS	Transcranial Magnetic Stimulation

Another major area of current research is that of *neuroscience*, which i.a. aims to explain mental processes in terms of brain-based physiology. The term mental collectively refers to psychological processes such as attention, perception, learning, memory, emotion and action (behaviour), with neuroscience providing the understanding of the underlying neural mechanisms of these processes. The activity of neurons is now known to depend on their very recent history (seconds), enabling them to modulate important aspects of both their structure and function, and this dynamic plasticity is a core property of the brain, sustained throughout the lifespan, and one that impacts significantly on the use and interpretation of measures of the brain-mind 'bridging' (physiology and mental boxes of Fig. 1). There is also an increasing awareness of the consequences of interactions between neurons in the brain, and mental processes in the mind, not only during early brain development, but throughout life.

Measurement of brain activity and *neuroimaging techniques* are leading to significant advances in our understanding of physiological processes involved in areas such as pain and pleasure perception, visual and auditory processing and the perception of taste and smell. These techniques include:

(a) electrophysiological methods (EEG/ERP and single-cell recordings) and magneto-encephalographic methods (MEG) that record the electrical/magnetic properties of neurons, and which provide excellent **temporal** information (the accuracy with which one can measure **when** an event occurs) from neuronal neuroelectric activity; and

(b) functional imaging methods (PET and fMRI), which record physiological changes associated with blood supply to neuronal populations that depend upon much slower haemodynamic responses, but provide much better **spatial** resolution (the accuracy with which one can measure **where** an event occurs).

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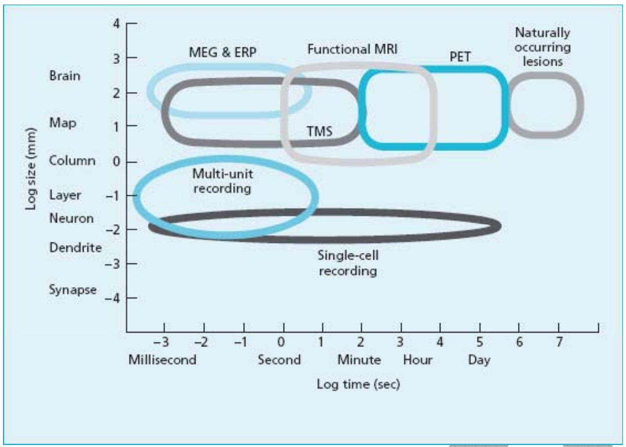

Figure 3. Spatial and temporal resolution of neuroscience methods.
Adapted from Churchland and Sejnowski.[19]

Non-invasive functional neuroimaging tools are now a cornerstone for basic neuroscience research and clinical diagnosis. Figure 3 compares the temporal and spatial resolution provided by the mostly widely used of these methods (the abbreviations are spelled out in the information box on brain activity and imaging techniques). At the level of whole-brain mapping there are two dominant neuroimaging techniques). At the level of whole-brain mapping there are two dominant neuroimaging techniques: EEG and fMRI. The former provides excellent temporal resolution, whilst the latter has excellent spatial resolution. Over the past few years, a concerted effort has been made to integrate these complementary neuroimaging modalities in an attempt to significantly enhance the spatiotemporal resolution significantly beyond that which is achievable by each technique individually. Furthermore, since neuroelectric (EEG) and haemodynamic (fMRI) signals reflect distinct but closely coupled features of underlying neural activity, combining EEG and fMRI data would allow the study of brain function from important different perspectives. Although combining these two techniques has proven to be technically very difficult, recent advances mean we are now beginning to see commercially available systems that provide for simultaneous EEG/fMRI recording. Much of this development has taken place in Europe.

One example of where this enhanced imaging capability is already being applied is in epilepsy research and diagnosis, where combined EEG/fMRI is proving to be a uniquely powerful tool for the study of spontaneous brain activity, such as during epileptic discharges. It is not possible to study this type of spontaneous effect by combining data collected in different sessions (e.g. EEG in one and fMRI in the other) since different patterns of activity are likely to have taken place in the two recording sessions. Therefore, simultaneous EEG-fMRI recordings are an absolute necessity for this type of study to be useful in MtI research. Furthermore, since perception and cognition depend not only on which brain areas are active, but also on how neuronal activity within each of those areas varies over space and time, these combined imaging techniques could find application for many other MtI problems. For example, they could be used to develop and test new computational theories of the neural processing underlying perception and cognition.

[19] Churchland, P. S., & Sejnowski, T.J. Perspectives on cognitive neuroscience, *Science*, 1988, 242 (4879), 741-745.

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Another example is stress research[20] where physiological stress responses may be both health-promoting and health-damaging. The brain communicates with the rest of the body, not only through nerves, but also through hormones and the immune system. Stress is often induced by mental and psychosocial conditions. In stress, powerful tools are needed for measuring the functions of cardiovascular and gastrointestinal systems but also sleep and breathing patterns and the effectiveness of the immune system as well as of the healing processes and feedback mechanisms accomplished by the brain. Useful MtI developments in stress research have for example taken place in the hormonal area, where cortisol measurements in saliva (e.g. hourly) have replaced the more long-term urine sampling (day and night).

2.3 The Mental World Perspective

What we see or hear or smell are all environmental perceptions, which are intimately related to the physiology of the perceiver and his/her intentions and activities. Perception may be passive (e.g. awareness of the immediate physical surroundings) or active (e.g., viewing the computer screen when composing, text). Active perception may be characterized as *purposive recognition*, which would involve intentionality, functionality and behaviour. Independent of the theoretical frameworks in which perception may be viewed as passive or active, it seems necessary that 'perceptual learning' is a prerequisite for being able to perceive. Marr[21] gives a passive definition of vision: 'a process that creates, given a set of images, a complete and accurate representation of the scene and its properties'. More recent views are that all our senses have a purpose, and that purpose is action. Action can be practical (motor control), theoretical (creation of a purposive representation, a decision or an internal change of state) or indeed aesthetic.[22] Originally, the active perception development had a very specific purpose, namely, that of designing visual systems or providing 'image space'. Forgetting about the other senses, visual processing became the model for perceptual processing.

The concept of a mental representation of a physical world can be illustrated with a few examples. We all experience that the external world is stable, despite it being perceived through highly mobile sensors (e.g. visual, acoustic, or somatosensory input). Attempts to link the external physical signals in the three-dimensional coordinates of the stationary world, to our correct perception and interpretation of them, have so far proved very difficult and have been far from successful. However, many new and important insights have been gained simply by framing the research problem differently, that is, by linking the sensory-internal representation of the physical signals to their 'downstream' interpretations. This in-between or mid-level representation indicates that the brain applies a fast coordinate transformation of the external signal, on command of the internal signal, which will guide the sensor's motion. Once the operating details of this representation are clarified, we can move on to approach the more basic question of how the brain achieves stable perception.

If the measured quantity consists of a self-report of a body perception or an emotional state, the processes that generate the information variable may interfere with processes in the 'measuring system'. Examples are the measurement of perceived intensity of chronic neuropathic pain (pain may be a mental condition though foremost located to a body area), or the measurement of the

[20] Lundberg, U. Stress, subjective and objective health. *International Journal of Social Welfare,* 2006, 15, Suppl. 1, 41-48.
[21] Marr, D. *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information*. San Francisco: Freeman, 1982.
[22] Sloman. A. On designing a visual system. *Journal of Experimental Theoretical Artificial Intelligence*, 1989, 1, 289-337.

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Essential Psychological Concepts

Attention	the act or state of attending esp. through applying the mind to an object or sense or thought
Mental	relating to the mind, its activity, or its products as an object of study; relating to spirit or idea as opposed to matter
Perception	a result of perceiving, a mental image (colour, odour, a piece of furniture, eventful sound)
Perceptual	of, relating to, or involving perception esp. in relation to immediate sensory experience
Cognition	to become acquainted with, come to know, the act or process of knowing including both awareness and judgment
Learning	knowledge or skill acquired by instruction or study
Memory	the store of things learned and retained from an organism's activity or experience as evidenced by modification of structure or behaviour or by recall and recognition
Emotion	the affective aspect of consciousness, a state of feeling (anger, fear, joy)
Mind	the element or complex of elements in an individual that feels, perceives, thinks, wills, and esp. reasons; the conscious mental events and capabilities in an organism
Consciousness	the quality or state of being aware exp. of something within oneself

feeling of happiness when wakening in the morning (emotion is foremost simply a mental condition). The philosopher Quine[23] would pursue that these two conditions (chronic pain and emotion) are information variables, which do not fulfil his criterion of objectivity. Objectivity can only be met by the principle of intersubjectivity, which means that at least another person makes the same measurement.

One criterion that is often stated as a prerequisite of an 'objective' measurement is that it must be possible for another person to quantify the measured parameter in exactly the same manner (this is the so-called 'principle of intersubjectivity'). This principle is firmly embedded in the measurement system for physical quantities, and indeed is a key driver behind the establishment of the SI system of units. But, in the field of perceptual measurements it is much harder to achieve (e.g., Stevens & Marks' magnitude matching or Ward's constrained scaling),[24] particularly if the measured quantity consists of a self-report of a body perception or an emotional state. For example, it is not possible for an external observer to make a measurment of the perceived intensity of chronic neuropathic pain experienced by a patient, although the patient himself can assign a numerical value to this pain (neuropathic pain may be a purely mental condition despite being perceived as though it is located in a specific body area).[25] Similarly, a person can measure their feeling of happiness when waking in the morning, but another person cannot quantify this in the same way. Psychophysicists have therefore proposed various ways by

[23] Quine, W.V. *Pursuit of Truth*. Cambridge, Mass.: Harvard University Press, 1990.
[24] Marks, L.E., & Algom, D. Psychophysical Scaling. In M.H. Birnbaum (Ed.) *Measurement, Judgment, and Decision Making.* New York: Academic Press, pp. 81-178
[25] Berglund, B., & Harju, E. Master scaling of perceived intensity of touch, cold and warmth. *European Journal of Pain*, 2003, 7, 323-334.

which to 'calibrate' perceptual quantities and thus fulfil the principle of intersubjectivity. These are usually either based on the use of descriptive categories to which a number is assigned[26], or involve the use of a set of defined reference stimuli against which the stimulus in question can be compared, that is, Berglund's master scaling.[27]

The visual system and its connection to mental processes is the most researched among the senses. Since the discovery of the receptive and perceptive fields in vision, it is still mostly unknown how the brain performs its primary visual analysis. Paradoxically, after successful early insights, the comprehension of higher visual functions (like the neuronal mechanisms for classification and identification of objects and faces) has proceeded faster and more successfully than the understanding of the early visual encoding/decoding mechanisms. Still, we are unable to build 'artificial systems' that can segment and detect visual signals as well as humans can. This is not for lack of technological know-how, but for lack of knowledge on how the (mental) perceptions are 'bridged' to human brain functions. It is high time to revisit this old problem again and try to solve it.

The major research aims for human vision would be to understand:

(1) how the architecture of the primary visual cortex encodes information,

(2) whether this architecture has also the capability to decode information, making the output directly available for decision and perception; and finally,

(3) how the decoded information is transmitted to other visual centres, and if this take place upon top-down request of signal or automatically upon a re-entry loop.

In the quest to understand these computations performed by the early visual brain, there is great hope and increasing evidence that such computations are modular and are repeated across multiple visual brain areas, and modalities.

An example of *canonical computation*[28] is the linear receptive field. It has been found to be a powerful description of neuronal responses in the visual system including the primary visual cortex, in the somatosensory cortex, and in the auditory cortex. Another example of *canonical computation* is divisive gain control and normalization, which is a key computation in the retina, thalamus, primary and associative visual cortex area. Divisive gain control has also been implicated in mediating adaptation, to adjust the sensitivity of neural systems to prevailing sensory statistics, thereby improving the quality of information encoded by a neural population code. Divisive gain control has also been shown to account for a wide variety of modulatory effects of attention and may play a key role in multisensory integration.

The multisensory character of affective signalling systems is seen in structures such as the amygdala, which plays a critical role not just in processing fearful facial expressions, but equally in other emotions, as well as in controlling large scale behavioural movements and auditory information.

[26] Borg, G. *Borg's Perceived Exertion and Pain Scales*. Champaign, IL: Human Kinetics, 1998.

[27] Berglund, B. Quality assurance in environmental psychophysics. In S.J. Bikabiwsju & G.A. Gescheider (Eds.), *Ratio Scaling of Psychological Magnitudes–In Honor of the Memory of S.S. Stevens*. Hillsdale, NJ: Erlbaum, 1991, pp. 140-162.

[28] For details of the concept of canonical computation see *http://www.theswartzfoundation.org/docs/Canonical-Neural-Computation-April-2009.pdf*)

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2.4 The Behaviour Perspective

Behaviour can be considered as the observable response a person makes to a situation. It may be regarded as the outcome of the processes described in Figure 1 and refers to the action or reaction of a human being in relation to the environment. Research on the behavioural relation–outer psychophysics–has been successfully applied in the study of human sensory systems, e.g. in understanding. Mathematical models play a central role in this very quantitative science e.g., signal detection theory, choice theory and theories of psychophysical measurement.

Behavioural outcomes can be of different levels of complexity, from the very simple example of moving the hand away from a source of heat-pain to, for example, body language and facial expressions. Body language in particular is a powerful expresser of human emotions and intentions. Without words being exchanged, a person's body language can attract or repel, signal welcome or create fear. It is a powerful mode of communication that is not well understood in objective scientific terms and there has been little research that would enable body language and its meaning to be 'measured' in a reliable way. However, this would be of great interest, since it has the potential to form the basis of more reliable tools for a variety of applications, ranging from detecting criminals and deterring terrorists to studying degenerative diseases. It is also generally agreed that body language plays a key role in successful negotiations and in achieving consensus in cultural, commercial, political and business transactions. Despite its importance, there has been little scientific research to support the intuitive feeling that body language is perceived and understood intuitively and effortlessly.

A further important aspect of behaviour, and the way in which behaviours and actions are perceived, is the influence of *learning*. The acceptability of certain behaviour is generally evaluated by social norms and the acceptability – or not – of a particular behaviour is something we all learn continuously during our life in new situations. The foundation for this knowledge is formed in the early years, based especially on learning from parents and in school. However, despite the importance of learning in all aspects of our daily life our understanding of how humans learn and adapt their behaviour, and our ability to measure and predict the effectiveness of different learning strategies – are still relatively underdeveloped. If, for example, childhood education is to move from the generic approaches currently used in schools to approaches that are optimized for the cognitive and emotional needs of each individual child, this will require the development of new measurment methods that can provide information about the subtleties that distinguish one child from another. One recent formulation of the nature of behavioural learning, and the practice of teaching, has led to a three stage educational model.[29]

(1) Technical assessment of the child's current conceptual basis for intellectually (in)appropriate action;

(2) Distinct and coherent reports of the components of the failures identified in Phase 1; and

(3) Specific tutorials designed to correct and reinforce appropriate behavioural efforts in respect of the original task. Repetition for this cyclical model provides continuous information about the child, and the appropriateness and effectiveness of individualised learning strategies.

Repetition of this cyclical model provides continuous information about the child, and individualized correctives to incoherence and error.

[29] Children's Progress Inc. holds the Patent (US 6,511,326 B1).

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3. Vision and Roadmap for MtI Research

3.1 Vision 1: New Types of Measurement Systems, Instruments and Models

The MtI research will develop measurement systems, instruments, and models that are grounded in internationally-recognised units and that allow for reliable quantification or prediction of phenomena which are intrinsically multidimensional, and which are mediated by human perception and/or interpretation. These will support new approaches to product design and development, value added and personalised products and services, improved health care, well-being and quality of life, etc.

3.2 Vision 2: Multidisciplinarity Becomes Interdisciplinarity

The MtI research is multidisciplinary in nature. It strives to become truly interdisciplinary. These two concepts have been defined as follows:

The Concept of Interdisciplinarity

'Interdisciplinary research requires more than having a group of individuals work side by side (= multidisciplinarity). They must, at a minimum, be fully cognizant of the methodologies and indeed the vocabulary of their colleagues.'

Göran Hermerén

The MtI research will develop an interdiscipline with common vocabulary and methodology by integrating knowledge on measurement systems, instruments, and models from its main disciplines,[30] as regards both (a) the knowing that–knowing that at the present time is stated in propositions (theories), and (b) the knowing how–knowing how to perform certain actions or operations (techniques). This will be accomplished by continued joint research, transfer of scientific knowledge, international creative interaction and cooperation among scientists from the different disciplines across application areas involved in MtI.

3.3 The MtI Roadmap

The overall vision and goals of the MtI research area is outlined in Figure 4, together with the specific research outputs necessary to achieve these, and the underlying areas of science and technology that are necessary in order to support the required research activities. The purpose of the roadmap is to provide an illustrative framework for MtI research and to emphasise the interdisciplinary nature of all stages of the work. The time scales shown are illustrative only, and should not be regarded as specific milestones. Similarly the research outputs and science and technology areas should not be regarded as definitive – others may be needed for, or result from,

[30] Levin, L., & Lind, L. (Eds.) *InterDisciplinarity Revisited. Re-Assessing the Concept in the Light of Institutional Experience*. Linköping, Sweden: OECD/CERI, 1985.

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specific MtI research projects. Furthermore, the inclusion of specific areas of science and technology in the roadmap is not intended to suggest that these are of relevance only to MtI (of course they have much wider importance than this), or that research in these areas should be funded under the 'umbrella' of MtI. Rather, further research in MtI will build on developments in these areas of science and technology, and support interdisciplinary activities so that they can be successfully applied for the specific purpose of achieving the MtI visions and goals.

An example will serve to demonstrate these points. Consider the case of the development of an instrument to emulate human odour perception. This forms part of the second box under 'research outputs' on the roadmap (Fig. 4), and will contribute to the achievement of the 'goals' and 'visions' by, for example, facilitating the measurement of unpleasant odours in the environment (quality of life benefits) and providing manufacturers of products such as foods and drink with new tools for quality control and design (improved industrial competitiveness). Such an instrument would require MtI research into measuring metrics, systems and instruments for specific aspects of human odour perception (e.g. 'lemon smell', 'onion smell', 'leather smell', etc.) – Box 4 of 'research outputs' on the roadmap, and this in turn would require measurements to understand human odour perception – Box 5 of 'research outputs' on the roadmap. The development of the instrument will thus require inputs from many different areas of science and technology, including sensors technology, data mining and modelling techniques, physical and chemical metrology, psychophysics, mathematics, engineering and neuroscience.

3.3.1 Roadmap: Enabling Technology Tools

There are a number of broadly based technology areas that need to be developed and applied in order to meet the goals of MtI research.

(a) Data mining and modelling techniques

Many developments have been made in this area in recent years which, for example, enable underlying trends in data to be identified, allow data from different inputs (such as different sensors or experimental set ups) to be effectively combined, and improve the ability to study correlations and relationships between different data sets. These are already proving invaluable for research related to measurements for human perception and interpretation. For example, leading edge data analysis tools, such as neural networks and LASSO (least absolute shrinkage and selection operator) regression have enabled researchers to identify the key physical parameters of samples of wood and textiles that are responsible for the complex perceptual attribute of 'naturalness', and novel image processing and pattern recognition methods are being used in 'iris recognition' systems to provide border control officers with new tools for identifying and recognising people. Further developments in the areas of data mining, image analysis and data modelling will continue to support the analysis of complex data sets of the type generated by MtI research, and give new insights into underlying perceptual and cognitive processes.

There is increasing interest in being able to understand human sensation and perception in terms of a series of basic computational modules: so-called 'canonical computation'. This idea is based on findings from sensory systems research, which strongly suggests that the brain may apply similar computations to different problems, and that the same computational processes are repeated across multiple areas of the brain and perceptual modalities (vision, audition, etc.). These canonical computations have been shown to be able to describe a wide variety of observed

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neurophysiological measurements and to apply at different levels of analysis (e.g., cellular, sensory systems, perception, cognition, emotion and behaviour). This approach has led to important simplifying insights into the relationship between neuronal activity and perception, and between neural computations and behavioural outcomes; without such simplifications, it would be almost impossible to understand the immense complexity of brain processes.

One area in which canonical computation has already had a significant impact is in the understanding of the human visual system, particularly in relation to higher visual functions such as the neuronal mechanisms for classification and identification of objects and faces. Nevertheless, despite these advances, we still cannot build artificial systems that can segment and detect visual signals as well as humans can, not for lack of technological know-how, but for lack of knowledge of how the human brain functions. Further developments are clearly needed.

Another application of canonical computation is in understanding abnormal brain function. It has been suggested that dysfunction of imbalance in canonical neural computations might underlie certain developmental disabilities (e.g., autism), neurological diseases (e.g. epilepsy) and mental illnesses (e.g. schizophrenia). In other words, the underlying cause for a diverse range of mental disorders could be a ‘computational failure’ in the brain. If this hypothesis is correct, then understanding the mechanisms and microcircuits underlying these neural computations could have important implications, and pave the way for new diagnostic procedures and treatments.

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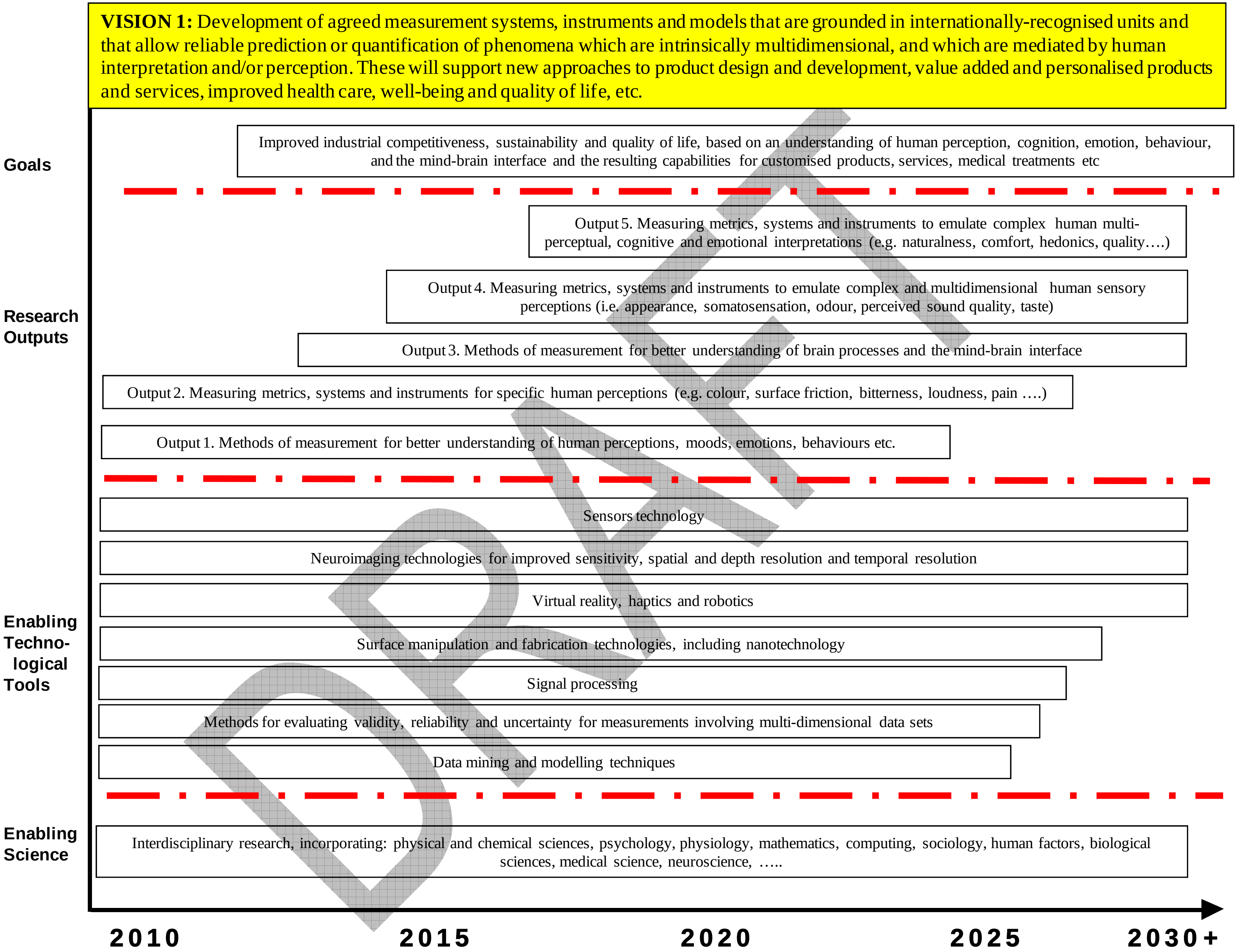

Figure 4. Diagrammatic roadmap for future research within the Measuring the Impossible (MtI) field.

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(b) Methods for evaluating validity, reliability and uncertainty for measurements involving multi-dimensional data sets

Basic ideas related to statistical analysis of data (standard deviation, confidence levels, t-tests etc.) are reasonably well entrenched in each of the scientific disciplines involved in MtI research. However, the individual disciplines have developed specific approaches and procedures for assessing the validity, reliability and uncertainty associated with the results that are generated, and this can make it difficult to draw meaningful conclusions when combining data from different areas of study. For example, much of sensory physics research involves the determination of correlations between physical data on the one hand, and perceptual responses on the other. The physical data has a stated uncertainty associated with it (with a defined confidence level), determined from analysis of the individual uncertainties associated with each of the variables in the measurement system and the use of rigorous mathematical procedures for combining these based on the theory of propagation of uncertainties. In the case of the perceptual data, the within- and between-individuals variances are usually treated separately and statistical techniques are typically used to determine the degree of internal consistency, test-retest reliability and the concordance among individuals (e.g. Cronbach's α, Pearson's coefficient of correlation, etc.). Conversely, in psychometry, interindividual differences in personality traits (depression) or states (e.g., mood) are measured with specially constructed psychometric tests,[31] which are standardized for a target population with specified reliability and validity.[32] If statistical regression analysis methods are used to investigate the correlations between the physical and perceptual data sets, it is important to appreciate that the outcomes from these depends critically on the uncertainties associated with the two sets of input data. These requirements are even more important when fitting more complex mathematical models to psychophysical data sets, which indeed seldom are rectilinear.

For all kinds of psychological measurement (incl. performance assessment), a general validity criterion or standard procedure is to determine the so-called construct validity. In lack of an operational definition, which is typically used in physics, the validity of psychological assessments may for example refer to content, external or consequential aspects.

Currently the different approaches to validity and uncertainty in physics and psychology mean that the degree of confidence is difficult to evaluate. Further work is therefore needed to ensure that latest best practice techniques can be consistently applied within the different disciplines and to allow reliable estimates of uncertainty for psychological models based on multidimensional data sets.

(c) Signal processing

Digital Signal Processing (DSP) is ubiquitous in modern measurement: the processing of measurement data by computers implies that at some stage a signal has been sampled and digitised. Much modern data acquisition and analysis software contains built-in functions for processes such as windowing, filtering and transforming signals, which are generally treated as black boxes by the user. However, these processes can introduce artefacts and additional sources of uncertainty into the results of measurements, which the experimentalist is either unaware of, or is unable to quantify. Uncertainties that arise from the choice and implementation of signal

[31] Lord, F.M., & Novic, M.R. *Statistical Theories of Mental Test Scores*. Reading, Mass: Addison-Wesley Pub. Co., 1968.
[32] Messick, S. Validity of psychological assessment. Validation of inferences from persons' responses and performances as scientific inquiry into score meaning. *American Psychologist*, 1995, 50(9), 741-749.

processing techniques are often not studied systematically and uncertainty budgets frequently omit contributions arising from these sources. Research is therefore required to: (a) ensure a more consistent and reliable approach to the analysis of effects such as resolution, sampling synchronisation and sampling jitter, and (b) to develop best practice procedures that are based on a clear definition of the measurement problem, good choice of algorithms and of numerical methods, and rigorous testing. The gap between average practice and best practice is wide, and is becoming wider as complex mathematical methods become more entrenched in DSP applications, and this could have serious consequences for the reliability and validity of research in the MtI area.

(d) Surface manipulation and fabrication technologies, including nanotechnology

For many areas of MtI research, there is a need to be able to produce materials with specific surface properties. For example, psychophysical investigations of visual properties (texture, pattern) require sample materials with well-controlled physical characteristics in order to explore the full perceptual gamut. Similarly, studies into the development of new instrumentation designed to mimic the tactile discrimination capabilities of the human fingertip require materials with surface features similar to human fingerprints. Considerable advances have already been made, such as modern laser etching and moulding techniques for plastic materials, that allow materials to be produced with specific surface features. New developments, such as nanotechnology, offer the potential for even greater control at finer levels of detail.

(e) Virtual reality, haptics and robotics

These areas of technological development offer the potential for new approaches to MtI research. For example, they allow investigation of human responses to well-controlled, consistent and well-characterised visual stimuli that are more realistic (and therefore provide responses that are more representative of real-world situations) than those that can be displayed on a flat screen display. Furthermore, they will be beneficiaries of MtI research, since by understanding better how the physical and mechanical attributes of objects affects the ways they are perceived, it will be possible to design virtual reality, haptic and robotic systems that reproduce these more comprehensively (giving a greater degree of realism). Major developments are already being made, such as flight simulators for training pilots and virtual surgery systems for training medical students in endoscopic surgical techniques, and these already, for example, allow study of physiological and behavioural outcomes under stressful situations. In another application area, the increasing use of sound visualisation systems combined with auralisation systems offer city planners (for the first time) the opportunity to design parks and building areas In terms of their soundscape and not just their visual appearance. As developments continue, more and more opportunities will arise for applying virtual reality systems in research to understand and produce human perception and cognition.

(f) Neuroimaging technologies

This is an area in which major advances have been made in recent years, which are offering unprecedented opportunities for exploring the functioning of the human brain. The introduction of fMRI systems, for example, is allowing brain activity to be studied while a perceptual task or cognitive decision is actually being undertaken. The fusion of EEG and fMRI techniques is likely to represent another significant development in neuroimaging techniques and to open up new opportunities for brain research, particularly with the increased demand for looking at the brain as an integrated yet highly plastic system. Developments are needed in this, and other (potentially

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completely new) neuroimaging technologies in order to allow brain functions to be explored with increased sensitivity and with greater spatial, temporal and depth resolution. These developments will lead to improved understanding of neural processes and clinical diagnoses and thus enhance our knowledge of how we process information and make decisions based on complex, multidimensional sensory inputs.

(g) Sensors technology

A key current challenge in sensor technology is the development of sensors with sufficient bandwidth and sensitivity to be able to tackle challenging dynamic measurement problems of the type encountered in the MtI research arena. Calibration and uncertainty evaluation for dynamic sensors can present major difficulties e.g. the information from a conventional (static) calibration cannot simply be applied to a dynamic situation because the signals generated from this calibration will have different properties from those encountered during the measurement. New methods are also needed to enable the recovery of signals from noisy or corrupted data and to allow the removal of the effects of the measurement system (e.g. the sensor system response) on the underlying signal. These so-called deconvolution methods must include consideration of the additional uncertainties that they may introduce, so that the final measurment uncertainty can be evaluated in a reliable and reproducible manner. Another challenge to be faced by MtI research lies in making sensors that can emulate the spatial capabilities of human sensory transducers. For example, in order to be able to measure the mechanical properties of materials in a way that is relevant for the human somatosensory system, it is necessary to develop force measurement sensors which not only have response characteristics that are similar to human skin mechano-sensors, but are also small enough to be used in matrix arrays with between-sensor spacing that is similar to that found in human skin. Such measurements are important because they have the potential to provide a more direct window what aspects of the physics of a material system can actually be sensed by the human somato-sensory systems and are therefore to contribute (however indirectly) to the creation of the perception. Advances in microelectromechanical systems (MEMS) offer the potential for meeting this need. MEMS devices generally range in size from 20 micrometres to a millimetre and usually consist of a central unit that processes data, the microprocessor and several components that interact with the outside, such as microsensors. At these dimensional scales, the standard constructs of traditional physics are not always useful. For example, due to the large surface area to volume ratio for MEMS, surface effects such as electrostatics and capillary action dominate volume effects such as inertia or thermal mass, and research will be necessary to address these issues.

3.3.2 Roadmap: Research Outputs

Output 1. *Methods of measurement for better understanding of human perception, mood, emotion, behaviour, etc.*

There is an urgent need for understanding how human perception, which relies on dynamic systems, works and how it is influenced by the various mental states of the perceiver. It is known that perceptual learning may improve for example the ability to differentiate between shades of colours, which means that the **perceptual competence** of the perceiver has improved. Moreover it is suspected that chronic pain patients and persons who have acquired sensitivities to certain chemicals have for some reason, increased their sensitivity as ‘measuring instruments’ of the relevant perceptions (potentially touch, warmth or cold, and odour). The sensitivity changes may

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be very large, as is for example the case in vision with dark-adapted eyes (= recovery from light). But they may also be very small, for example, if the human olfactory system has adapted to pulp mill odours; but, the sense of small may still be keen in detecting odorous substances not present in this exhaust, at very low concentration levels. The incredible capability of olfaction in dogs exemplifies well how skilled the sense of smell can become. After several days, they can trace which directions game have moved, This would require recognition of dynamic broad pattern change at extremely low concentrations.

Still other examples are from the study of emotions, where for example the visual perception of an emotionally disturbing scene is able to generate very different results (disgust or hilarity) depending on the internal state of the perceiver and the external conditions perceived in the environment where the scene happened. A general mental psychophysical approach should be developed that can relate the internal state to the mental representation. Both internal and mental representations could then be associated with physiological and/or psychophysical and/or cognitive variables, but the underlying model will hopefully be the same.

Whereas we can control precisely the physical stimulus, we cannot correspondingly control the internal state representation. This is a dynamic representation that will depend strongly on recent and past history and it would require a **dynamic system analysis.**[33] Compared to sensor instruments, the dynamic representations have great potentials for improving discrimination and providing special environments for sensory measurements.

None of the traditional (and well founded) objections or stumbling blocks on the road to a science of emotions has disappeared. Thus, measuring emotions in a scientific way is a problem as overwhelming as it was thirty years ago. This is astonishing, as many new tools and techniques have become available over the last decade allowing refined physiological measures as well as detailed spatial and temporal information from brain imaging methods. All these methods are now widely available so it is now important to understand what the current obstacles are to affective neuroscience. It may be noted that current models of affective processes are almost exclusively centred on how we perceive faces. But the face is very limited channel of affective communication, often restricted to situations of face-to-face communication at fairly short distances. We need to ask whether the major theories and associated neurofunctional models that are currently available generalize to many other situations of affective communication and behaviour. It may also be that the problem is that measuring emotions as mental phenomena is still too crude.

The benefits of better methods of measurement for human perception, mood, emotions, behaviour etc. are

- Clinical applications, particularly diagnoses of chronic pain conditions, as well as potentials for diagnosing any condition based on a constellation of symptoms such as non-allergic conditions suspected to have an environmental origin like ‘multiple chemical sensitivity’ or ‘sick building syndrome’.
- Environmental applications such as testing emission of building materials for indoor air environments (olfaction, perception of skin senses, symptoms).
- City planning as regards soundscapes in parks and auralisation as a method to enhance the understanding of city plans and consequences for future soundscapes.

[33] Ward, L.W. *Dynamic Cognitive Science*. Boston, Mass.; MIT ’A Bradford Book’, 2002.

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- To be able to research the benefits of aesthetics, positive thinking, and positive emotions for human health.

Output 2. *Measuring metrics, systems and instruments for specific human perceptions (e.g. colour, surface friction, bitterness, loudness, pain …)*

In order to be able to communicate and specify specific perceptual attributes of materials, objects and environments in a consistent and reliable manner, it is first necessary to develop an appropriate set of measurement metrics (or a 'language'), together with the related instrumentation and analysis systems to enable these metrics to be evaluated. For example, in the area of visual appearance a suite of colorimetric weighting functions and colour appearance models have been developed that can be used to describe the colour of materials, rather than using detailed spectral data, and these are now used throughout the world for scientific and industrial applications. The establishment of such measuring metrics, systems and instruments will require better understanding of specific perceptual responses (Output 1) together with the development of:

(i) Sensors and instruments that can measure at an appropriate degree of resolution, related to the capabilities of the human sensory receptors; and

(ii) Data analysis and processing systems that can take the outputs from the sensor/instrument and convert these to numbers (metrics) that relate to human perceptual responses with quantifiable validity, reliability and uncertainty.

For example, detailed characterisation of visually-complex materials (materials whose appearance varies over the surface and/or with the angle of illumination and view) requires multi-spectral and goniometric measurement approaches. These are at an early stage of development at various institutes, but need considerable further advances in instrumentation, and improved reference standards, in order to provide fully validated measurements. These measurement systems will generate huge datasets, potentially many Gb in size. If this information is to be useful for comparison and specification of a required visual appearance, metrics must be developed that allow these large arrays of data to be reduced to a discrete set of visually meaningful variables describing specific properties such as 'sparkle' or 'woodiness' (in the same way that it is possible to specify 'colour' in terms of three numbers representing the relative proportions of red, green and blue light reflected from, or emitted by, a surface). Furthermore, it must be possible to quantify the measurement uncertainty associated with these new metrics, systems and instruments so that they can be used in a reliable manner for specification and comparison purposes.

The development of these metrics, systems and instruments for measuring and quantifying specific human sensory perceptions is not only a necessary stepping stone towards the ultimate goal of measurements to emulate complex perceptual-cognitive and emotional outcomes, but will also bring its own benefits, including:

- Improved industrial competitiveness, by allowing designers and manufacturers to specify, evaluate and compare the perceptual attributes of different materials on a reliable and consistent basis. They will be able, for example, to compare materials from different suppliers to obtain the most cost effective options, ensure that supplied materials meet the required specifications and design criteria, evaluate improvements made during product

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R&D, maintain the quality of their manufacturing processes and products, and provide consumers with information so that they can make informed purchase decisions.

- Better product design, through capabilities to optimise the design for specific perceptual attributes. The functional and aesthetic design of products is the key distinguishing feature between products and companies, and is one of the main criteria used by consumers when deciding what to buy; improved design is therefore a critical consideration for all areas of the economy. In the fashion industry, for example, designers often develop the colour and pattern for the fabrics they wish to use using computer graphics, but the appearance of these on the screen is typically different from the appearance of the printed fabric; as a result, most designers still rely on swatches of material to act as 'references' for the final design. A better system for specifying colour appearance would avoid this problem.
- Reduced reliance on consumer panels during product development, leading to reduced time to market and lower development costs. In addition, consumer panels provide only an assessment of those designs that were part of the study; they do not directly provide ways to generalise from the experimental data to new designs and also do not include any constructive way of generating new designs. Developments in measuring systems and metrics for specific perceptions that are based on physical characterisation will provide the necessary predictive capabilities.
- Reduced counterfeiting and product piracy, through the inclusion of security features that are readily perceived by consumers but are difficult or expensive to replicate (note the damage done by counterfeiting and product piracy is estimated to be 5% of the world trade or 200 billion EUR.[34] This is particularly important for high value products and printed documents e.g. measurement systems for perceptual responses could facilitate improved detection of counterfeit currency by the general public.

Output 3. *Methods of measurement for better understanding of brain processes and the mind-brain interface*

Recent advances in understanding human brain function have been aided by the introduction of new powerful imaging and recording techniques, such as fMRI, high-density EEG, neuronal recording from awake monkeys and neuronal-computational methods. These methods open the possibility to investigate separately the various serial neuronal processes that lead from the sensation of physical signals to their perception and interpretation. It is now well accepted that the sensory and a good deal of the perceptual analysis takes place early, probably separately from interpretation, evaluation, behaviour and decision making. The overall process can, consequently, be subdivided into three major steps: (i) the physiological representation of the phenomenon (ii) a mental representation of the phenomenon that includes its interpretation and (iii) is followed by subsequent behaviours and decisions.

At present we are still in the early stages of the development of methods and techniques to allow quantitative linkage between the sensory/physiological inputs and their mental representations. Improved computational/mathematical methods are required that will open new quantitative ways to understand the mind the way it processes information. This will bring benefits particularly in areas where the input to the mind and the interpretation/decision that this engenders is not simply

[34] OECD Study: *Economic Impact of Counterfeiting*, 1998.

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associated with a physical signal (i.e. a straightforward sensory perception), but includes internally generated signals, such as memory, intentions, expectations, emotions or language and semantic-syntactic structures. As indicated previously (Section 3.3.1 (a)), approaches such as canonical computation offer the potential for significant simplifying insights into the relationship between neuronal activity, sensation, perception, cognition, and behavioural outcomes, and these will be essential if we are to build reliable models of human interpretation and decision making. They may also leas to advances in our understanding of brain malfunctions, such as autism and schizophrenia, and so underpin new diagnostic procedures and treatments.

Output 4. *Measuring metrics, systems and instruments to emulate complex and multidimensional human sensory perceptions (i.e. visual appearance, somatosensation, odour space, soundscape, taste)*

Having developed metrics, systems and instruments for measuring specific human perceptions of materials, objects and environments (e.g. colour, surface friction, bitterness, loudness – Output 2), the next step is to be able to combine these to emulate complex perceptions across a given modality. In other words, to develop techniques to link individual sensor perceptions to provide a multidimensional sensory outcome (flavour, appearance, etc.). This will require better understanding of human perceptions (Output 1) and human brains processes (Output 3), as well as developments in sensors, signal processing, data mining and modelling, and techniques for evaluating reliability and uncertainty (building further on similar developments required for Output 2). It is likely that capabilities for appearance and soundscape will be the first to be fully developed, since these are the best understood human senses at present.

These new metrics, systems and instruments will lead to positive impacts through better industrial competitiveness, improved produce design and reduced reliance on consumer panels, as described under Output 2 above. By being able to combine individual perceptions to provide a complete assessment of a sensory response, it will be possible to make further improvements in each of these areas of benefit. For example, it will be possible to balance and optimise any potentially contradictory requirements in the target design criteria, such as a need for a material that is perceived as being both ‘smooth-to-the-touch’ and ‘non-slippery’.

Output 5. *Measuring metrics, systems and instruments to emulate complex human, cognitive and emotional interpretations that are based on multiperceptual inputs (e.g. naturalness, comfort, hedonics, quality…).*

The final stage in the achievement of Vision 1 of the roadmap is the ability to make measurements that emulate, and allow predictions of, complex multi-perceptual, cognitive and emotional interpretations of objects, environments and situations that are based on multi-perceptual inputs, perceptions across different modalities and enable evaluations to be made of complex outcomes such as perceived naturalness, comfort, hedonics and quality. This will have many beneficial impacts, building on those given under Output 2 and Output 4 above and including:

- Increased industrial competitiveness through better product design, including the capability to design for individual preferences and target consumer perceptions, e.g. an ability to measure and predict the perceived qualities of different materials will allow

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manufacturers of products as diverse as furniture, mobile phones, fashion accessories and clothing to select the optimum material for different target markets without the need for expensive and time-consuming panel tests.

- Improved sustainability and reduced wastage of limited natural resources e.g. by being able to measure the perceived naturalness of synthetic wood materials, and thus develop synthetic materials which are perceived as being ‘natural’ but have improved durability, it will be possible to reduce reliance on highly valued materials such as teak and rosewood and so help to conserve these limited natural resources.
- Better quality of life for specific groups of society such as the elderly or those in hospital e.g. capabilities for measuring the comfort of different textiles will support the design and manufacture of improved bedding materials (sheets, pillowcases etc.) for the bedridden.

The necessary developments will build on all the previous Outputs and will involve all of the technology and science areas outlined earlier.

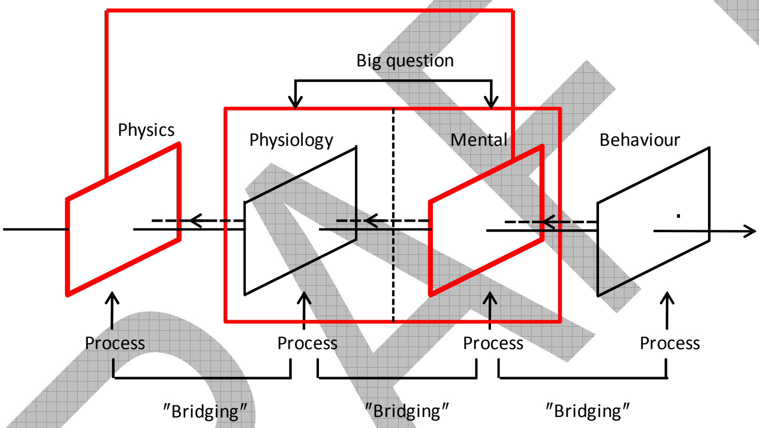

Figure 5. Illustration of the measurement skin-senses perceptions in chronic pain patients.

3.3.3 Roadmap: Example 1: Chronic Pain

To measure the perceptions of touch, warmth, heat or heat pain in patients with chronic pain requires on the one hand (a) specific theory of the chronic pain patient as a measuring instrument (as compared with healthy persons) and on the other (b) a procedure for calibrating the various measurement scales obtained from single pain patients. Depending on the type of chronic pain condition, one or more skin senses (warmth, cold and touch) may be affected. For example, fibromyalgia may be diagnosed, in the most painful spots of the skin, by aberrant cold perception and normal warmth and touch perception. Neuropathic pain is a chronic condition located to a *delimited skin area* where the nerves have been damaged and one or more of the three senses have become dysfunctional. The perception of the skin senses of warmth, cold and touch in the same skin area are affected and may on an individual basis be aggravated or attenuated by controlled physical stimulation. Instead of measuring the quality and/or intensity of the pain as such, neurologists rather base their diagnosis on abnormal function of the three skin senses. The perceptual qualities of warmth, heat and heat pain are assumed to be parts of the same quantity, here named perceived intensity of warmth.

Master scaling, grounded in magnitude estimation, is used as the method of measurement of perceived intensity of warmth in skin areas of patients with neuropathic pain and corresponding skin areas of healthy controls. A case-control experiment is first conducted. Each patient or control scales perceived intensity of warmth in the pain-affected area and in two control areas (area contralateral to the pain area and the thenar–palm of the hand). The stimulations consist of ca. 15 temperatures generating neutral to heat-pain perceptions and presented in random orders. Perceptions in contralateral skin areas are used as an *internal* reference scale (comparator) for each patient's or control's measurement scale. The empirical scales obtained for the pain-unaffected thenar are used for master scaling perceived intensity of warmth to a master scale. Thus, thenar provides a scale of perceived intensity of warmth from all patients and controls that can be used for *calibrating* the other measurements. This thenar scale is obtained from an identical skin area unaffected by the neuropathic pain condition.

The theory is that chronic neuropathic pain is a condition, which changes the sensitivity in pain-affected skin areas.

3.3.4 Roadmap: Example 2: Product Quality

There are numerous different perceptual characteristics that determine the overall perceived quality of a product, such as functionality, appearance, how it feels to the touch, sustainability, comfort etc. These features are inherently related to the product but are currently only measurable with the aid of human subjects. It would be possible to develop a system for evaluating or quantifying overall product quality based on a weighted combination of perceptual evaluations for each of these individual attributes, but this is not only time-consuming (requiring a large number of perceptual panel tests) but also cannot be developed without actually building the product and asking people for their opinions. Furthermore, it is not possible with such a system to predict what changes should be made to the design in order to improve the perceived quality (or indeed the perception of any of the contributing attributes). In other words, it is very difficult to move away from a 'trial and error' approach for enhanced product quality, which is the standard and time-honoured approach that most companies use to develop a new product. (Note that some new approaches are being developed (e.g., conjoint analysis),[35] that build on the basic ideas of perceptual evaluation but instead of varying one attribute at a time, vary them in combination; by measuring the subjective responses to these combinations, it is possible to deduce the important components driving specific perceptions. However, although such multi-variable approaches may be more amendable to generalisation than traditional approaches, they still suffer from the need to conduct large numbers of panel tests using extremely large number so samples.).

Perceived product quality also depends on the combined effect of many different physical attributes e.g. tensile strength, hardness, barrier properties, colour, texture, surface roughness, chemical composition etc. These properties are also inherently related to the product, but (unlike perceptual attributes) are measurable with appropriate physical or chemical measuring instruments. A system for evaluating or quantifying overall product quality based on a weighted combination of these physical characteristics would have the advantage that it could be used to predict the effects of changes in the design without the need for expensive, and time consuming, user trials. In order to establish such a system, however, it is necessary to be able to relate the physical properties of the product to perceived product attributes – this is a major goal of MtI

[35] Moskowitz, H.R. Creating new product concepts for foodservice – the role of conjoint measurement to identify promising product features. *Food Service Technology*, 2001, 1, 35-52.

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research. One possible approach to the development and application of such a predictive model for perceived product quality is shown in Figure 6. (Note that the diagram is grossly simplified particularly in terms of understanding and allowing for the complicating factors that might need to be considered when applying this approach in practice, such the effects of expectation, the influence of the price of the product, and cognitive manipulations such as the use of word 'fresh' in marketing, etc.).

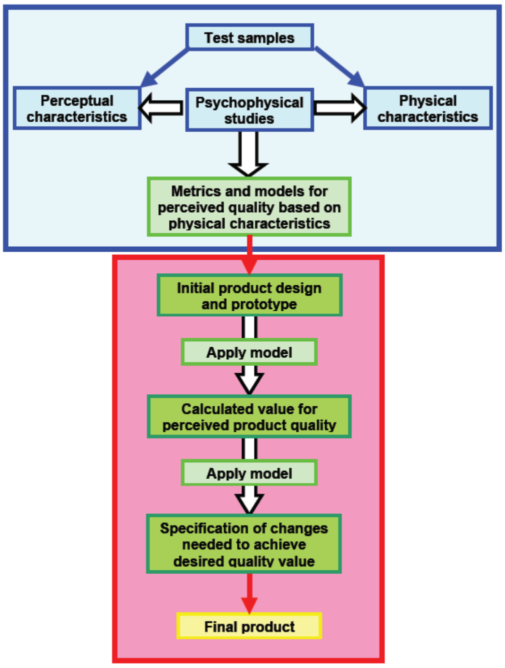

Figure 6. Example of development and application of a predictive model for product quality. Blue shaded box is MtI research. Pink shaded box is product design and manufacture.

The development of metrics and models for perceived product quality based on the associated physical characteristics would require interdisciplinary research in the area of MtI. This could then be applied during the product design process to remove the need for iterative prototyping and user trials, leading to benefits such as reduced time to market and lower development costs.

4. How to Achieve the Vision

As discussed in earlier sections, 'Measuring the Impossible' requires interdisciplinary measurements of quantities and qualities that are dependent on human perception and/or interpretation. Such measurements are based on natural and social sciences, are complex and have to be integrated in ways that are far from established. One of the key questions to be addressed for MtI research is to what extent is it possible, or even desirable, to apply the approaches used in physical metrology to other areas of MtI? Is it useful to apply concepts such as traceable calibration, internationally agree measurement standards and scales, rigorous uncertainty evaluation, and independently reproducible measurement results, the considering quantities and qualities that are dependent on human perception and/or interpretation? Is it possible to establish reliable calibration protocols and reference standards in areas such as psychophysics, cognitive neuroscience, body language, and emotion research? (Note that psychophysicists have already started to develop various ways by which to ‘calibrate’ perceptual measures, using descriptive categories to which a number is assigned, or sets of defined reference stimuli against which the stimulus in question can be measured.) The approaches used in physical metrology, particularly the ideas behind the development of the SI system of units, may provide an important framework around which to build future research in MtI. However, they may equally impose an unwarranted straitjacket and restrict innovative developments in the area if thoughtlessly or needlessly applied. These issues need careful consideration and may be differently addressed or implemented in future MtI research, depending on the application in question.

The Programme initiated by the European Commission in FP6 has acted as an important catalyst in bringing researchers from diverse disciplines such as physics, physiology, psychophysics, psychology, and neuroscience together in a way that has not been done previously. The outcome has been successful as evidenced by some groundbreaking achievements under MINET And the associated MtI research projects. However, the whole area is at a relatively early stage of development and requires the involvement of a wider group of stakeholders and researchers. The research is naturally of high risk and requires support from public funds.

The challenge now is to keep the momentum and to build on the achievements of the first phase. This is difficult as under FP7 all support for research is channelled through the Thematic Programmes. These focus on technology and /or industrial sectors, making it difficult to support truly interdisciplinary work such as that promoted in this report. Therefore, the Expert Group makes the following recommendations to the EC:

- Develop combined Thematic Calls in selected priority areas of research;
- Provide funding under Co-ordinated Actions for the MINET network so that researchers can maintain contact and develop co-operative research activities with support from national and trans-national sources;
- Consider the inclusion of this type of work under the COST initiative;
- Ask the JRC Institute of Perspective Technological Studies, Seville, to review the potential opportunities and benefits of a new EC initiative in this area.
- Hold a cross DG workshop with the Expert Group to review the outcome of projects supported under ‘Measuring the Impossible’ Programme in FP6 and potential opportunities for the future.

In addition, the MINET network members should consider:

- The possibility of establishing a dedicated peer-reviewed scientific journal to promote research and development in ‘Measuring the Impossible’ field;
- The establishment of an Annual Conference with support from core MINET members.

In conclusion, the vision presented in this report is highly ambitious and challenging with the aim of creating new and demanding interdisciplinary knowledge in the form of novel integrated theories covering natural and social sciences. Our view is that this is not only ‘nice to have’ but absolutely ‘essential to have’–from a cost-benefit as well as a science-benefit perspective. The risks associated are high and unprecedented, but the benefits and impacts will be large and research support from public funds at the early stages will be vital.

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