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Chapter 10

Objectifying the Subjective: Fundaments and Applications of Soft Metrology

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Additional information is available at the end of the chapter

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Abstract

The aim of the interdisciplinary research was to facilitate the understanding of a specific topic passing by different disciplinary perspectives. Soft metrology is the perfect example of a scientific field that needs that sort of approach. Seeking to provide a reproducible basis for qualifying and quantifying what are essentially 'soft' measurements (subject to human perception and interpretation) is a particularly challenging scientific endeavour. This chapter presents a theoretical overview of main concepts around soft metrology and, in the second instance, proposes a mathematical model for the measurement of a soft measurand through a dedicated index (IPER—influence on performance index).

Keywords: soft metrology, human perception, human–machine interaction, human performance

1. Introduction

> *'Metrology must be ideal, but practical. Rigorous, but accommodating. Demanding, but forgiving. Quantitative, but qualitative. Forward-looking, but faithful to the past'.*
>
> (John Michael Linacre, University of Sydney, 2005).

This work represents both a compendium of ideas around soft metrology intended as the set of techniques and models for measuring quantities related to perception. The knowledge of the physical world through senses is a key topic of the history of philosophy. Since Plato and Boethius, passing through all the history of Greek and Indian ancient philosophy, getting to the modern era with Descartes and Hume until reaching contemporary philosophy of mind,

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human perception has always been a central topic of thought as a key epistemological problem. Hereby, some specific theoretical interpretation of the relation between humans and the physical world will be presented, depending on how much they are useful to the foundations of a specific line of reasoning pertinent to the metrological scope.

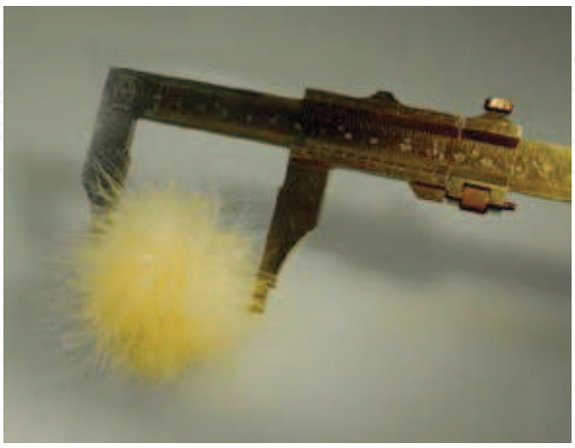


Figure 1. A metaphorical picture for soft metrology. The traditional tools/methods of metrology are not suitable for measuring quantities related to human perception.

The soft metrology expression is relatively recent and has appeared in literature the first time in 2003 in a report of the National Physical Laboratory [1] where it has been defined as 'the set of techniques and models that allow objective quantification of the properties determined by perception in the domain of all five senses'. It can be intended as the investigation about the correlation between the human subjective response and objective measurement of physical properties of the empirical world.

The main objective of this work is to contribute to the definition of the theoretic basis, the language and investigation methodology related to soft metrology. Some methodological proposals are presented as well as some experimental findings. Subjective and physiological subjects' responses to specific visual and auditory stimuli are considered, in conditions of low or high cognitive load and with an environmental setting influencing the perceptual process (presence of glare or noise). Here lies also a good question into what extent one mode of perception is affected on influenced by another, as in perceiving the flux of information coming from the empirical world cross-modal interactions normally occur (**Figure 1**).

As a matter of fact, the recent interest in metrology of perception by the industry for design and development of efficient human–machine interfaces makes the study of these issues promising interesting developments. Human–machine interface (HMI) is in fact out of the niche of basic scientific research and hi-tech applications (e.g. military, aviation and aerospace), thus making key service for consumer goods. This is attested by the recent identification of commercial brands with the HMI, for example in the automotive industry (in 2004, Citroen ASL for the notice of passing the line of road through seat vibration and APGS Lexus' 'Advanced Parking Guidance System', in 2006 Fiat 'Blue & Me', in 2009 the Toyota Head Up

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Display). Soft metrology, together with cognitive science and ergonomics, can define the criteria necessary for effective planning and efficient industrial design as well.

As the aim of the interdisciplinary research is to facilitate the understanding of a specific topic passing by different disciplinary perspectives, soft metrology is the perfect example of a scientific field that needs that sort of approach.

Seeking to provide a reproducible basis for qualifying and quantifying what are essentially 'soft' measurements (subject to human perception and interpretation) is a particularly challenging scientific endeavour. The tentative to do so has been carried out by the work of MINET [2,3] as described below, in a pure and fruitful interdisciplinary perspective. An expression of this key aspect of research in this area is to involve, for example investigations of human mental and brain 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).

Human perception and 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.

'Measuring the Impossible' is the impressive title of a recently concluded European call for new and innovative research projects, concerning the measurement of quantities and qualities related to human perception and interpretation.

As a matter of facts, many phenomena of significant interest to contemporary science are intrinsically multidimensional and multidisciplinary, with strong crossover among physical, biological and social sciences. Economic aspects, products and services appeal to consumers according to parameters of quality, comfort and beauty which are mediated by perception and culture.

A few examples of funded projects can help to get the feel of recently closed or still on-going research activities in this area.

The MONAT project [4], Measurement of Naturalness, coordinated by the National Physical Laboratory (NPL, United Kingdom), was aimed to measure the naturalness of materials, such as fabrics, on the basis on of their visual appearance (influenced by factors such as colour, texture, gloss…) and tactile feeling (thermal conductivity, hardness, friction coefficient…). Investigations into this multisensory perception and interpretation require the measurements of related perceptual, physical and psychophysical qualities and their combinations.

CLOSED [5], closing the loop of sound evaluation and design, coordinated by the Institut de Recherche Acoustique/Musique (IRCAM, France), sought to improve products by introduc-

ing, at the early design stage, information concerning the perceived sound quality of products in use.

Inspired by the MINET activities, a book on this topic has been published in 2011 and this has been the first comprehensive publication to scrutinise this measurement topic from a multi- and interdisciplinary perspective [6].

2. Fundaments of Soft Metrology

2.1. Definition and theoretical context

As far we know, the first appearance of the expression 'soft metrology' and its related definition appeared in 2003 in the NPL Report CMSC 20/03 [1]. Here, soft metrology is defined as follows:

> *The set of measurement techniques and models which enable the objective quantification of properties which are determined by human perception.? (The human response may be in any of the five senses: sight, smell, sound, taste and touch). Thus, soft metrology includes aspects of appearance (colour and gloss), noise quality, texture of food (such as creaminess) and, more broadly, topics such as biometrics and usability of systems.*

Here, the author points out that soft metrology, in its extended sense, is not yet an established branch of metrology, and today, it does not find a unique place within the structure of the National Measurement System of each country.

That does not mean that measurement scales do not exist or that research in the domain of soft metrology is not conducted, but rather that there is a lack of metrology research in considering properties of human perception and cognition as measurand of physical properties of the environment.

As a matter of facts, soft metrology requires the measurement of proper physical parameters and the development of models to correlate them to perceptual quantities. Traceable soft metrology is achievable both through the traceable measurement of the physical parameters and the development of accurate correlation models.



Figure 2. A set of boxes that are perceived to increase in SIZE: the corresponding physical measurement is of LENGTH (for example, in metres).

As an example, we would like to mention the following one, described in the NPL Report as quite explicatory of the soft metrological approach when a relation to physical stimuli and perception is investigated.

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The example considers the perception and measurement of length. A series of boxes are perceived to increase in size (**Figure 2**). A human observer could be asked to indicate a number correlated to their impression of the size. Equally, a device could be constructed (a ruler) which could be used to 'measure' the size of each square, that is its area.

In this case, it is likely that the human responses, the soft measure, will simply correlate with the measurements made using the ruler, the physical measure. Hence, soft metrology can be considered the formulation of a correlation between the human response and the physical measure.

As a second example, consider the series of boxes shown in **Figure 3**.



Figure 3. A set of boxes that differ in a systematic manner.

To the human observer, something is changing as the boxes are examined from left to right—but what is it and how can it be described? Some may call it lightness, some brightness, some density.

It has been shown [7] that human observers, after a little training, can give a consistent response to the changes they see. Equally, some physical measures, for instance, the reflectance of the paper surface of every square, the density or even their luminance, can be made of each box using a suitable metre, and a scale constructed that relates the two measures.

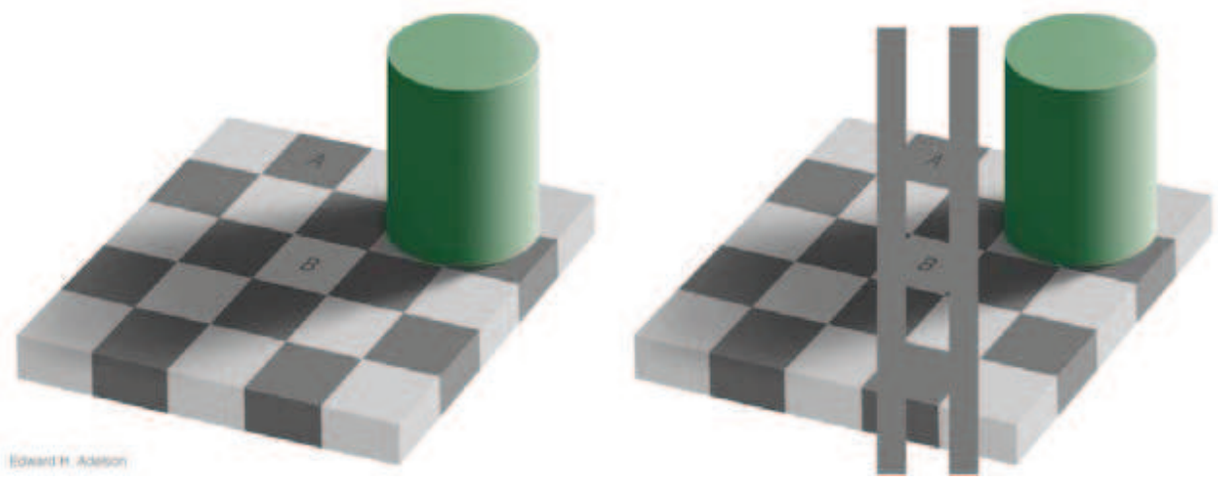


Figure 4. The squares marked A and B are the same shade of grey.

Also, in real life, the human response is not absolute as a physical measure usually is, but it is subjectively correlated to a real or imaginary reference. This fact creates a set of interesting

optical illusions, as the famous Checker illusion [8], a visual illusion published in 1995 by Edward H. Adelson, Professor of Vision Science at MIT (**Figure 4**).

Differently from the human eye, a physical system does not find luminance differences between square A and B in **Figure 4** and cannot understand the presence of the chessboards without complex elaboration of the image. The visual system is not very good at being a physical light metre, but that is not its purpose. The important task is to break the image information down into meaningful components, thereby perceiving the nature of the objects in view.

We now go rapidly through the idea of what it does imply for considering the human senses as a measuring instrument and what measuring the act of perception means. Following what said just before, soft metrology can be considered as the investigation of the correlation between human, subjective, responses and physical, objective, measures. What is generated is a measurement scale, a number series, which allows the subjective response to be predicted from the objective measure.

There is a parallelism between the process of perceiving and the one of measuring. This comes from the idea that human senses can be considered a sort of transducer. A transducer is, in fact, a tool that turns a physical quantity—as a sound pressure wave—in another physical quantity—as a voltage variation. It is assumed that the transducer has a well definite function between input and output quantities (i.e. linear) and can be calibrated, but in the case of the human being, of course, this attribute cannot be proposed.

As a matter of facts, the human being is already equipped himself with transducers (sight, hearing, smell, taste and touch) and should be considered as a filter or rather, using the language of signal, such as a black box through which a stream of input events, perceived by the senses, flows through leading to opinions, actions and output reactions.

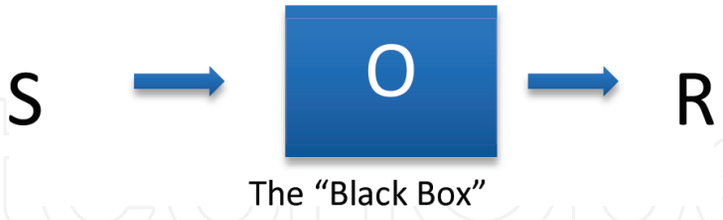


Figure 5. The input–output model by behaviourists. The internal functioning of on organism mind (O) generates a response (R) to a stimulus (S).

This idea is borrowed from the thought of a certain strand of the early twentieth-century psychology called behaviourism. When coming to the study of human and, more broadly, its measurement, behaviourists concentrated exclusively on the study of behaviour neglecting the study of the inner workings of the mind as considered impossible to be measured in a scientifically objective way.

In contrast, behaviours, or actions produced by organisms, as external events, were regarded as objects clearly quantifiable and measurable. **Figure 5** shows the model stimulus-response

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(SR) that represents the behaviourist position. In the model, a stimulus (S) in the environment affects an organism (O) and the stimulus then causes the body to produce a response (R).

In this model, the human mind is not shown. The perceiving subject is treated just as a black box, possessing unfathomable properties and internal relations impossible to be explained. In this perspective, he becomes simply an entity that is used to convert the stimuli into responses. A mathematical model between S and R can be developed using experimental results, but the model should be true only in this specific condition and eventually could not be linked to the real process involved in O.

However, the father of behaviourism, John B. Watson (1878–1958), [9] admitted himself that the decision not to investigate the sphere of mental activity was mainly caused by the limited instruments available in his time. Behaviourism was, in fact, the dominant paradigm in psychological research for nearly 50 years until the advent of cognitive science in 1960.

Therefore, while behaviourism meant the mind as a passive body operating according to simple rules of conditioning, cognitive psychology saw in it a strong, active ability, such as the selection of information from the environment and, about prior knowledge, the capability of act on the results of such selection. Fundamentally, there are three main reasons that led to the rapid growth of this new perspective:

- the failure of behaviourism in explaining language acquisition;
- the invention of new measuring devices to examine the mental activity;
- the advent of the computer and hence the widespread use of the metaphor of the mind computer.

The emergence of new investigation devices, including positron emission tomography (PET), computed tomography (CT) and magnetic resonance imaging (MRI), but also the increased use of computers, was the innovations that have most contributed significantly to the decline of behaviourism.

Psychologists realised that the mind, like a computer, could be treated as a device that represents and transforms information. This initial metaphor then flew into the actual conception of the human mind as an information processor and of the act reasoning assimilated to computing, in which the behaviourist stimulus-response model turned into input–process–output one:

- input: incoming information in mind, corresponding to the 'stimulus' of behaviourism;
- process: information converting that change and are reworked by mental processes evolving continuously with experience;
- output: output information in the form of behaviour, language, facial expressions, posture, etc., corresponding to the 'answer' or 'reaction' of behaviourism.

According to Ulric Neisser (1928–2012), an American cognitive psychologist, the study of man:

> *refers to any process in which sensory input is transformed, reduced, elaborated, stored, recovered and used* [10]

and all these modes convey exactly the meaning of the numerous potential of the human mind in the management of information from the sensory world.

Summarising, if behaviourism had the fundamental claim to limit the psychological investigation of objectively observable reactions, its strength was in the methodological need that it asserted: it is not possible to scientifically talk about what escapes any possibility of objective observation and control.

If at that time it was not possible to have this kind of control over mental processes, which is no longer the case thanks to the modern techniques of physio-neurological investigation, with the addition of the contemporary cognitive science assumption that human rational processes can be considered as an algorithm.

After this short glimpse on some relevant ideas of theories of human perception, we now go through more specific issues related to soft metrology as a part of metrological science and therefore bound to its specific approach.

2.2. Research issues and challenges

The main research issues that are currently central to the soft metrology area [11] can be grouped into three main categories:

- foundation and theory;
- instrumentation and methods;
- implementation areas and applications.

Several foundational and theoretical issues are of primary interest in the soft metrological field. These include as follows:

- language and terminology;
- concepts of measuring system (or instrument);
- the issue of measurability and uncertainty.

Language has been a major issue in twentieth-century scientific and philosophical debate. In the metrology community, an extensive revision of linguistic terms has been undertaken, starting with the publication in 1984 of the International vocabulary of basic and general terms in metrology, now at its 3rd edition [12].

As suggested [13], in any revision of terms, a revision of concepts and theories must also be considered and this would indeed be beneficial for the entire world of measurement. From a theoretical point of view, soft metrology can be assumed funding its basis on the Representational Theory of Measurement [14] where measurement is defined as

> *a process of empirical, objective assignment of symbols to attribute of objects and events of the real world, in such a way as to represent them or to describe them and also, in a shortest form, as the correlation of numbers with entities that are not numbers* [15].

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In this theory, values are assigned based on correspondences or similarities between the structure of number systems and the structure of qualitative systems. A property is defined as 'quantitative' if such similarities can be established.

The concept of measurement is often misunderstood as merely the assignment of value, but it is also possible to assign a value in a way that is not a measurement. For example, a value of a person's height can be assigned, but unless it can be established that there is a correlation between measurements of height and empirical relations, it is not a measurement. To link this theory with the soft metrological research field [16], it is interesting to cite the following passage by an article by Luce and Suppes [17].

> *In the 75 or so years beginning in 1870, some psychologists (often physicists or physicians turned psychologists) attempted to import measurement ideas from physics, but gradually it became clear that doing this successfully was a good deal trickier than was initially thought.*
>
> *Indeed, by the 1940s a number of physicists and philosophers of physics concluded that psychologists really did not and could not have an adequate basis for measurement. They concluded, correctly, that the classical measurement models were for the most part unsuited to psychological phenomena. But they also concluded, incorrectly, that no scientifically sound psychological measurement is possible at all.*
>
> *In part, the theory of representational measurement was the response of some psychologists and other social scientists who were fairly well trained in the necessary physics and mathematics to understand how to modify in substantial ways the classical models of physical measurement to be better suited to psychological issues.*

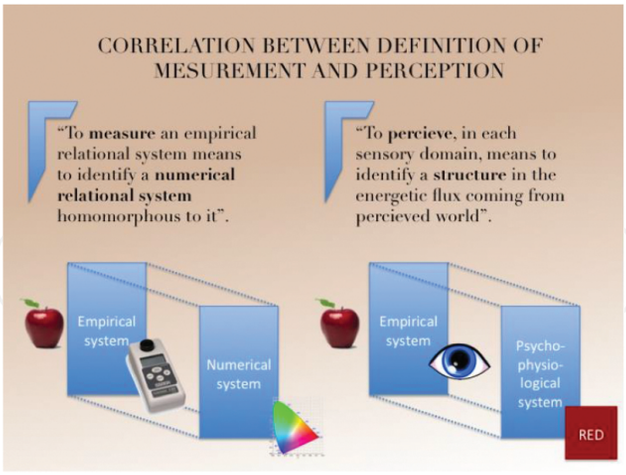


Figure 6. The two definitions of *measure* and *perceive* and streamlined representation of the passage from real word to numbers and percept through a measuring instrument (e.g. a colorimeter) or a sense (e.g. sight).

As a matter of facts, an actual correlation between the definition of measure—as coming from representational theory—and perceive [18] does exist (**Figure 6**). Both measuring and perceiving are an act of correlation between two systems.

The measuring process consists of the creation of an image (in logic: homomorphism) of the real world into a numerical system or model that maintains its proportions and inner relations, through the use of an instrument or model.

The act of perceiving can be assumed to function in the same way: from empirical stimuli, the human mind creates an interpretational model that represents proportions and relations in the real world, through the use of senses.

Concerning measurement uncertainty, a basic issue in soft metrology is to come to terms with how to handle inter-individual differences in measurement. These may be considered true differences, as postulated and measured in psychometrics, or they may be regarded as common and specific errors in measurement, as treated in psychophysics.

Instrumentation-oriented research involves the measurement of external physical events (stimuli) that more or less simultaneously give rise to perceptual and physiological (or behavioural) responses. It would include the perception and interpretation of processes and the development of sensors that, to a certain extent, would mimic human perception and interpretation.

Consider, for example, the measurement of sound. Highly accurate measurement microphones and binaural recording devices, those allow acoustic stimuli to be measured as they appear at the input of the auditory system, have been developed [5]. Sophisticated binaural reproduction or surround sound systems, with processors and algorithms, provide the required signal processing.

As concerns vision, not only luminous intensity and colour wavelengths can be measured, but also parameters of the interaction between light and matter, and surfaces properties, such as texture-topography, involving sophisticated signal processing [4]. Similar considerations also apply to the other senses.

As previously mentioned, measurements related to human perception and interpretation have a wide range of actual and potential applications [19]. Here, the areas of perceived quality (of products and services), environment, ergonomics, safety, security and clinics are briefly mentioned.

In the first part of the last century, the impact of mass production was so high that qualitative aspects of goods were somewhat neglected. Today, the shortage of energy sources and the concern for pollution may increase the demand for durable, high-quality goods. Thus, perceived quality, which results from the perception and interpretation of sensory input, may play a key role in the industrial competition. Examples of products include food, materials, simple and complex devices. A good cup of coffee, for example, is appreciated on the basis of a combination of taste, smell, sight, touch and, for the Italian recipe, of the colour of the surface cream [20].

As said, much of human behaviour is controlled by responses to the five senses. To the consumer, the whole appearance (that can be the smell, the sound, the taste…) of specific products, whether natural or man-made, is used to assess quality, both consciously and subconsciously, and hence mediate product choice.

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Providing a means for reproducible measurement of parameters (such as pleasure and pain) has important implications in evaluating all kinds of products and services.

In the commercial world, a host of factors—from naturalness, aesthetics and comfort to security, service and price influences choice and gives peculiarities to a brand. Is the smell of a new car appealing for the customer? Does a fabric have a luxurious feel?

By being able to predict user perceptions and reactions through a robust modelling, can allow to save time and costs by meeting the expectations of the customers, without the need for extensive and expensive testing.

The ISO 9000 framework, however, requires the parameters able to characterise products to be measured in a precise way, together with associated tolerances, to establish a formal quality-control system. Normally, this is more easily done using instruments because of their inherent controllability, stability and repeatability. The challenge of soft metrology is to gain a comparable level of strengths.

3. The three-output model

The fundamental question to which soft metrology attempts to provide answers may be described as follows: given as input a sensory stimulus metrologically quantifiable (a special sound, a flash of light, the roughness of an object, etc.), what is the outcome of the interaction between this and humans? That is, what is the measurable output, if it exists, of this interaction?

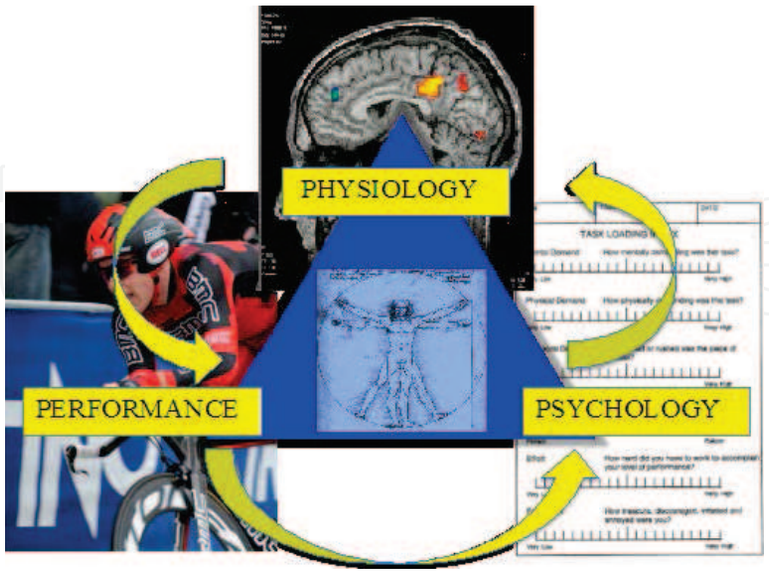


Figure 7. A schematic representation of the three-output model. Measuring the interaction between man and the objects or events of the real world means to take into account three kinds of outcomings from physiology, from evaluation of performance and psychology.

To answer this question, the output of the perceptual interaction between subject and world objects or events shall be defined at first. According to the tools and analytical models available, three main outputs (**Figure 7**) have been identified [21]:

- physiological output,
- performance,
- psychological output.

The first output coming from human–world interaction is called 'physiological', and it can be quantified through various clinical techniques that monitor some physiological parameters considered as important indicators of changes in the level of perception, emotion or cognition (e.g. the measurement of heart rate, blood pressure, pupil dilation, sweating, brain electrical activity).

The second output is referred to human performance (we will refer to it also as 'operational') and is quantified by measuring the changes in the attitudes of a subject doing a particular task. These can be for example attention, fatigue or accuracy and can be assessed via various parameters, such as reaction times, the number of correct answers, test duration, etc.

The third output is determined and quantified by evaluation scales, questionnaires and interviews (we will refer to it as the 'psychological' output), and this is one of the most popular methods for subjective data acquisition. The response of subjects to a specific question about their opinion on a particular aspect of a stimulus is defined 'psychological' as it is mediated by the psychology (culture, mood, prejudices…) of the person to whom the question is asked.

The method of investigation proper to soft metrology must consist in the comparative analysis of these three main outputs. Through an organic synthesis of these data, is it possible to get reliable objective information about the subjective response to a particular sensory stimulus [22]. An example of analysis of this sort will be given through the description of the influence on performance (IPER) index, correlated by a numerical example explicating its applications.

Before moving further, it is important to introduce a review of key terms of the three fields of investigation. When necessary they are redefined in order to incorporate in the soft metrological terminology, the three-output model approach.

3.1. Redefinition hypothesis and terminology

As previously mentioned for what regards soft metrology is necessary to establish a common language and a definition of key terms to simplify the organisation of concepts of this new branch of metrology. Hereby, a list of important terms is given with the related definitions congruent with the model given by the last edition of the International Vocabulary of Metrology [23].

A first and remarkable tentative is the review by Goodman about the measurement of physical parameters in sensory science [24]. Goodman summarises the definitions and descriptions of some relevant physical parameters useful for soft metrological applications. As we interact with our environment, and with objects within that environment, through our five senses, the

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physical measurements that are most relevant for sensory science are those relating to the parameters that are sensed by our sensory transducers. As reported in Goodman's article, these are listed in **Table 1**.

The object of the subjective measurement is the interaction between a subject and the physical word, and the schematic representation of **Figure 8** shows the interaction between subject and physical word displaying the key terms and expressions that is important to define.

Sensory modality	*Physical parameter and SI units*	*Sensory response*
Vision	***Luminance* (candela per metre squared, cd·m^{-2}):** light reflected from or emitted by a surface	Brightness
	***Gloss* (dimensionless):** light reflected in specific directions relative to the incident direction	Shininess
	***Chromaticity for non-self-luminous surfaces* (dimensionless):** spectral reflectance of surface combined with spectral irradiance of illuminating light source	Colour
	***Chromaticity for self-luminous surfaces* (dimensionless):** spectral radiance of surface	Colour
	***Dimensional characteristics* (metre, m):** length, volume, etc.	Size and shape
	***Chroma, saturation, hue and other colour appearance measures* (dimensionless):** derived from spectral reflectance and spectral radiance/irradiance measurements, defined in terms of various colour measurement systems	Colour appearance in the context of the visual environment
	***Goniometric and spatial surface characteristics* (dimensionless):** spectral reflectance as a function of position and angle combined with spectral irradiance of illuminating light source as a function of position and angle	Visual texture and pattern
	***Light scattering characteristics* (dimensionless):** spectral transmittance as a function of position, angle and thickness	Transparency, clarity, haze, translucency
Touch	***Surface topography* (metre, m):** height of surface as a function of position	Roughness/smoothness
	***Friction* (Newton, N):** force experienced when moving a fingertip over the surface	Stickiness, slipperiness
	***Hardness*(dimensionless):** resistance to indentation (measured on various defined ratio scales)	Hardness
	***Tensile strength, elasticity* (pascal, Pa, or newton per metre squared, N·m^{-2}):** resistance to deformation	Stretchiness, bendability, drape, compressibility
	***Thermal effusivity* (joule per metre squared per kelvin**	Coldness, wetness

Sensory modality	*Physical parameter and SI units*	*Sensory response*
	per square-root second, $J \cdot m^{-2} \cdot K^{-1} \cdot s^{-½}$ or watt square-root second per metre squared per kelvin, $W \cdot S^{½} \cdot m^{-2} \cdot K^{-1}$): ability of a material to exchange thermal energy with its surroundings	
Sound	***Acoustic pressure*** **(pascal, Pa, or newton per metre squared, $N \cdot m^{-2}$):** sound wave amplitude	Loudness
	Acoustic intensity **(watt per metre squared, $W \cdot m^{-2}$):** sound power per unit area	Loudness
	Acoustic frequency **(hertz, Hz):** sound wave frequency	Pitch, sharpness, tone quality, timbre
	Acoustic impedance **(decibel, dB—note this is accepted for use with SI, but is not an SI unit):** attenuation of sound waves through a medium	Muffled
Taste and smell	***Chemical composition*** **(mole per metre cubed, $mol \cdot m^{-3}$)**	Flowery, fruity, salty, sweet, bitter, sour….

Table 1. Key physical parameters for sensory transduction as reviewed by T. Goodman (2012), pp. 59–60.

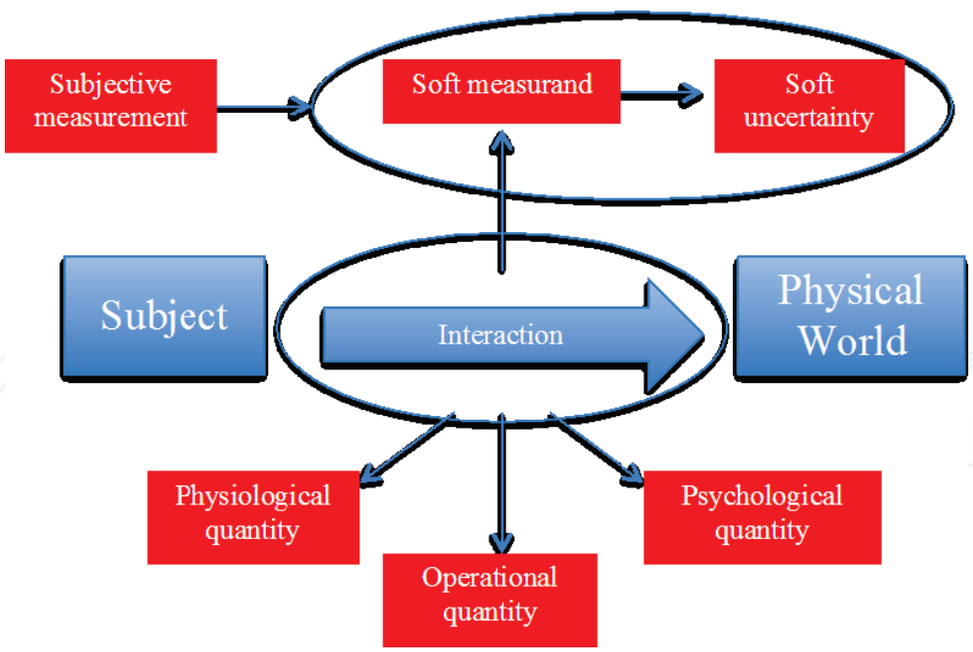


Figure 8. Schematic representation of relationships between key terms in the description and measurement of the interaction between the subject (S) and the physical world (PW).

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Subject: human being directly involved in the subjective measurement process (an interesting parallelism is the definition given in VIM: 2008—3.8 of sensor: element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured).

Soft metrology: set of models and techniques that allow subjective measurements intended as the process of experimentally obtaining one or more quantity values that can be attributed to human physiological, operational and psychological quantity—as defined by soft metrology—directly involving one human being.

Subjective measurement: process of experimentally obtaining one or more quantity values that can be attributed to human physiological, operational and psychological quantity—as defined by soft metrology—directly involving one human being.

Physiological quantity in soft metrology: property of a phenomenon belonging to human body that has a magnitude expressible as a number and a reference.

Operational quantity in soft metrology: property of a human-centred task that has a magnitude expressible as a number with proper unit of measurement, in terms of distance (difference) from an optimal or ideal execution of the same task.

Psychological quantity in soft metrology: property of the attribution of a judgment by a human to an object, event or phenomenon—concerning his/her opinions, emotions and sensations—that has a magnitude expressible as a number and a reference in a given scale.

Soft measurand: a characteristic of a specific object to be measured, in a specific situation. This object outcomes from the interaction between a human and the physical world—event not necessarily repeatable and directly quantifiable—and related to perception, cognition and volition.

Soft uncertainty: non-negative parameter characterising the dispersion of the quantity values being attributed to a soft measurand.

Intrasubjective repeatability: comparability level of subjective measure under a set of repeatable measurement conditions, related to the same subject.

4. Influence on performance (IPER) index

4.1. IPER index definition

We give now a formulation proposal within the soft metrological field of research, as we developed a set of experiments aimed to investigate how noise can affect the performance of humans involved in a task. However, the primary object of these kinds of studies is more general and lies in the possibility of testing a theoretical method of analysis peculiar to soft metrology. The idea is to acquire a robust tool that permits a reliable interpretation of subjective responses to sensorial stimuli and get a quantification of non-metrologically definable objects, such as the 'influence of external stimuli on human performance'. To get this quantification,

three kinds of outputs—coming from subjective measurement—have been identified as significant. They are characterised as described hereinafter (**Figure 9**).

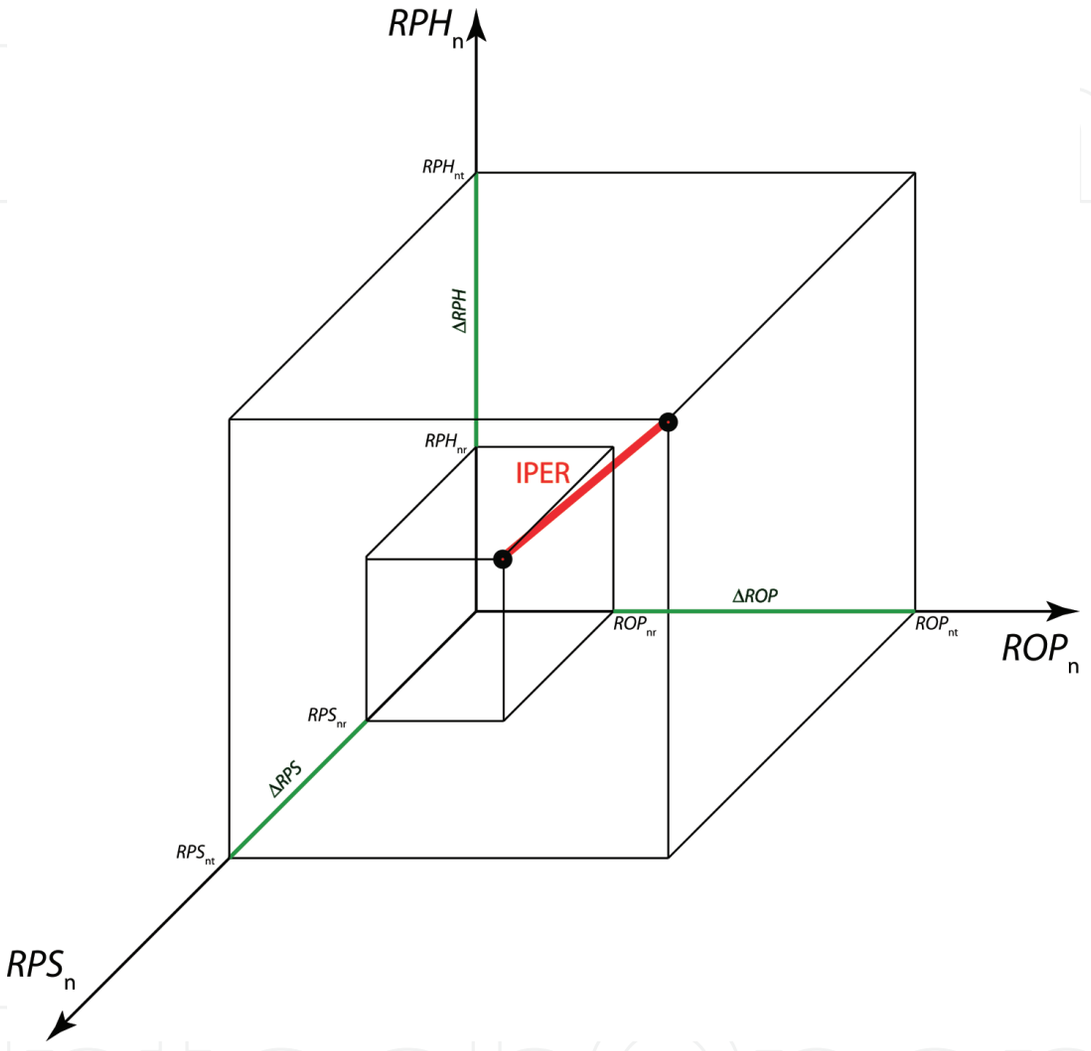


Figure 9. Geometrical description of IPER.

The idea of synthesising in a single number these three outputs in a significantly and properly weighted way comes from the need of metrologically describe a complex and variegated object of study or, in general, what is called soft measurand. Due to its specific synthesising nature, such single number allows prompt and easy comparisons between different complex and multifaceted conditions, events or setups where several subjective parameters are involved. This single number is the here-proposed IPER index.

The main characteristic of IPER index is that all its components are dynamically weighted in order to picture—as plausibly as possible—the actual behaviour of the interaction between a subject and a stimulus together from a physiological, operational and psychological point of

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view. The 'influence on performance' is the soft measurand considered, and this influence can be due to different phenomena or events from time to time.

The IPER index combines the three outputs R described before:

RPH = Physiological output;

ROP = Operational output;

RPS= Psychological output.

The physiological output (from now RPH) is the first output coming from human-–world interaction, and it can be quantified through various clinical techniques that monitor some physiological parameters considered as important indicators of changes in the level of perception, emotion or cognition (e.g. the measurement of heart rate, blood pressure, pupil dilation, sweating, brain electrical activity). It depends on:

1. the subject;
2. other influencing external parameters:
    1. the test stimulus;
    2. other stimuli imposed as constants;
    3. stimuli present during the test that are erroneously considered as non-influencing and that are not controlled;
    4. experimental methodology (e.g. the order in which the subject carries out some tasks part of the experiment).
3. measurement uncertainty:
    1. referred to the subject;
    2. referred to stimuli;
    3. referred to measurement instruments used for the measure of the physiological parameter.

The operational output (from now ROP), is referred to human performance and is quantified by measuring the changes in the attitudes of a subject doing a particular task. These can be for example attention, fatigue or accuracy and can be assessed via various parameters, such as reaction times, number of correct answers, test duration, etc. It depends on:

1. the subject;
2. evaluation method: the parameter chosen for evaluation the performance (e.g. response time, errors percentage…);
3. difficulty of the task assigned to the subject:

    objective (e.g.: memorising a list of five digit or nine digit) and

subjective (e.g.: memorising a list of number in a language that for the subject is the native or not);

4. measurement uncertainty associated to the evaluation method chosen:
    1. instrumental;
    2. subjective (learning and fatigue).

The psychological output (from now RPS) is the subject's response to a specific question about his opinion on a particular aspect of a stimulus, determined and quantified by evaluation scales, questionnaires and interviews. This specific output is evaluated through the subject's reply to a question about his opinion on the perceived quality of the performance in doing the task given. RPS depends on:

1. the structure of the questionnaire;
2. the subject's interpretation of each question (a good questionnaire should avoid as much as possible the influence of personal interpretation of questions and terms on subject's answers. Anyway, this is a kind of bias that, even if not considered, must be mentioned as reputedly existent);
3. the subject's answers reliability (e.g. same answer to same question posed in a different time of the test);
4. the subject's capability of evaluating proportions.

As IPER aim is to combine together these three R, in order to make them comparable, a normalisation procedure is needed.

The normalisation criteria chosen consist in determine the measurability range (R_{MIN} and R_{MAX}) for each R and then reconduct each R to a range between 0 and 1. Measurability range can be the one given by literature (e.g. the pupil can dilate from a minimum of 2.2 mm to a maximum of 7.9 mm), or derive from test conditions (e.g. regarding the percentage of errors we have 0% corresponding to any error and 100% corresponding to any correct answer). On the other hand, different kinds of ranges, and therefore normalisation criteria, can be chosen. For example, it is possible to choose as measurability range the minimum and maximum values reaches by the specific set of subjects involved in the experiment (e.g. regarding the percentage of errors we impose a minimum of 20% deriving from the performance of the subject that in the test group did the best, and the same with the maximum of 85% deriving from the worst performance). Another possibility could be to set measurability ranges on the parameters of each subject, but of course in this way IPER will not be directly comparable between different subjects.

In order to go from each R to the corresponding R_n (where R_n stands for 'normalised output'), the following linear procedure is adopted, but more complex normalisation rules could be adopted too:

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$$RPH_{\mathrm{n}} = \frac{RPH_{MIN} - RPH}{RPH_{MIN} - RPH_{MAX}}$$

$$ROP_{\mathrm{n}} = \frac{ROP_{MIN} - ROP}{ROP_{MIN} - ROP_{MAX}}$$

$$RPS_{\mathrm{n}} = \frac{RPS_{MIN} - RPS}{RPS_{MIN} - RPS_{MAX}}$$

Each one of these output (R_n) corresponds to a parameter monitored in a reference condition (r) and in one affected by the presence of an influencing phenomena (t). So, after the normalisation procedure, we obtain the following six a-dimensioned parameters:

$$RPH_{\mathrm{nr}} \qquad RPH_{\mathrm{nt}}$$

$$ROP_{\mathrm{nr}} \qquad ROP_{\mathrm{nt}}$$

$$RPS_{\mathrm{nr}} \quad RPS_{\mathrm{nt}}$$

Where:

the subscript 'nr' means normalised response in *'reference'* condition, that is the condition where the task done by the subject is supposed not influenced by something external.

the subscript 'nt' means normalised response in *'test'* condition, or the condition where the task done by the subject should be affected by the presence of something external (i.e. disturbing, distracting, annoying…).

Then, in order to compare the two conditions, the difference between the two kinds of outputs (reference and test) is considered:

$$\Delta RPH = RPH_{\mathrm{nt}} - RPH_{\mathrm{nr}}$$

$$\Delta ROP = ROP_{\mathrm{nt}} - ROP_{\mathrm{nr}}$$

$$\Delta RPS = RPS_{\mathrm{nt}} - RPS_{\mathrm{nr}}$$

where

Δ*RPH* = Finite increment between physiological response in test condition and the physiological response in reference condition.

Δ*ROP* = Finite increment between operational response in test condition and the operational response in reference condition.

Δ*RPS* = Finite increment between psychological response in test condition and the psychological response in reference condition.

After the normalisation and the calculation of the difference between reference condition and test condition, IPER is:

$$\text{IPER} = \sqrt{\Delta RPH^2 + \Delta ROP^2 + \Delta RPS^2}$$

IPER goes from a minimum value of 0 to a maximum value of v3. In order to obtain a more legible and directly understandable value, IPER is then transposed to a scale between 0 and 100 using the following formula and becoming $IPER_{0,100}$.

$$IPER_{0,100} = 100 \cdot \frac{IPER}{\sqrt{3}}$$

Mathematically, the IPER index is the Euclidean distance between two points in a 3D Cartesian space where the axis are the normalised physiological output (RPH_n), operational output (ROP_n) and psychological output (RPS_n).

The first point represents the test results in reference conditions (r), the second point in test conditions (t). If the subject responses show no differences between the two testing condition, the $IPER_{0,100}$ index is 0 (i.e. no measurable influence on performance). If the differences are the maximum permissible for each response (depending from range chosen for each parameter), the $IPER_{0,100}$ index will be 100.

Using a scalar index makes easier the evaluations of differences, but information on the contribution of the three outputs is lost. This aspect is described after where a vectorial version of IPER is given.

At the same time, the IPER index is very effective for comparing the influence of different external stimuli. A similar approach is adopted in colorimetry to quantify colour differences using the CIE Laboratory colour system. In the CIE Laboratory system, the difference between two colours is given as the distance between their representation on a 3D space where the axes are correlated with lightness, chroma and hue. Where *lightness* is the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting; *chroma* is the colourfulness, of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting; *hue* is the

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attribute of a visual sensation according to which an area appears to be similar to one of the perceived colours, red, yellow, green, and blue, or to a combination of two of them [25].

The last issue regarding the IPER index has to do with the fact that the final value looses the information regarding the contribution of each single component to the final result. For example, two subjects in a specific experiment reach an $IPER_{0,100}$ value of 48 but the first deriving especially by the fact that he made lots of mistakes in the given task and the second especially because of a great physiological reaction. In order to highlight this differences and at the same time understand the dynamic of the experiment, the computation of the percentage of importance of each *R* on the final $IPER_{0,100}$ value is required.

So, given the previous example, the first subject can have an IPER = 48, composed for the 10% by physiology, 60% by performance and 30% by psychology, while for the second subject the same value is composed by 70% physiology, 5% performance and 25% psychology.

These values are computed as follows:

$$IPER_{\text{ph}} = 100 \cdot \frac{\Delta RPH^2}{IPER^2}$$

$$IPER_{\text{op}} = 100 \cdot \frac{\Delta ROP^2}{IPER^2}$$

$$IPER_{\text{ps}} = 100 \cdot \frac{\Delta RPS^2}{IPER^2}$$

Where:

$\boldsymbol{IPER_{ph}}$ = percentage of importance on $IPER_{0,100}$ value of the physiological parameter;

$\boldsymbol{IPER_{op}}$ = percentage of importance on $IPER_{0,100}$ value of the operational parameter;

$\boldsymbol{IPER_{ps}}$ = percentage of importance on $IPER_{0,100}$ value of the psychological parameter;

4.2. Numerical example and uncertainty evaluation

Suppose the following experiment: the subject A is involved in a mnemonic task (e.g. memorise and repeat the correct order of a set of numbers), while an environmental disturbing factor is present (e.g. acoustic noise at two different levels). In reference condition, the acoustic noise is not present. The soft measurand is the influence of noise on mnemonic performance. The three outputs are:

Parameter	Measurement unit	Range		Measured value	Uncertainty	Range	Normalized value	Results	
		Min	Max					Value	Uncertainty
RPH_r	mm	2,2	7,9	5,0	0,10	-5,70	0,49		
RPH_t				6,1	0,11		0,68		
ROP_r	%	0	100	80,0	0,00	-100,00	0,80		
ROP_t				52,0	0,00		0,52		
RPS_r	1	0	10	8,0	0,29	-10,00	0,80		
RPS_t				5,0	0,29		0,50		
ΔRPH	mm							0,19	
ΔROP	%							-0,28	
ΔRPS	1							-0,30	
$IPER$	1							0,45	0,06
$IPER_{ph}$	%							18,1	9,1
$IPER_{op}$	%							38,1	9,8
$IPER_{ps}$	%							43,8	14,1
$IPER_{0,100}$	1	0	1,73					**26,2**	3,4

Table 2. Spread sheet of $IPER_{0,100}$ for subject A, in test condition 1.

- ***RPH*** corresponds to the measurement of pupil diameter;
- ***ROP*** corresponds to the percentage of correct answer in the mnemonic task;
- ***RPS*** corresponds to the answer to the question 'How much well you did your task?' from 0 to 10 (where 0 means 'very badly' and 10 means 'very good').

The measuring range for these three *R* is:

- for ***RPH***: 2.2 ÷ 7.9 mm corresponding to physiological dilation range of a healthy pupil [26];
- for ***ROP***: 0 ÷ 100% corresponding to the percentage range of correct answer; and
- for ***RPS***: 0 ÷ 10 corresponding to the answer scale range to the question 'How much well you did your task?'.

These conditions are considered:

- **Reference condition:** Mnemonic task in silent condition;
- **Test condition1:** Mnemonic task in the presence of background noise of type1;
- **Test condition2:** Mnemonic task in the presence of background noise of type2.

As shown in **Table 2**, for the subject A in test condition1 $IPER_{0,100}$ is 26.2 ± 3.4 (a detailed description of how uncertainty is calculated is given in the following paragraph § 5.3).

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Parameter	Measurement unit	Range		Measured value	Uncertainty	Range	Normalized value	Results	
		Min	Max					Value	Uncertainty
RPH_r	mm	2,2	7,9	5,0	0,10	-5,70	0,49		
RPH_t				6,2	0,11		0,70		
ROP_r	%	0	100	80,0	0,00	-100,00	0,80		
ROP_t				40,0	0,00		0,40		
RPS_r	1	0	10	8,0	0,29	-10,00	0,80		
RPS_t				3,0	0,29		0,30		
ΔRPH	mm							0,21	
ΔROP	%							-0,40	
ΔRPS	1							-0,50	
IPER	1							0,67	0,06
$IPER_{ph}$	%							9,8	4,7
$IPER_{op}$	%							35,2	6,6
$IPER_{ps}$	%							55,0	8,5
$IPER_{0,100}$	1	0	1,73					**38,9**	3,6

Table 3. Spread sheet of $IPER_{0,100}$ for subject A, in test condition 2.

In **Table 3**, the value for $IPER_{0,100}$ in test condition 2 is calculated. The subject A shows a similar physiological reaction to test condition1 but a different behaviour for what regards operational and psychological parameters giving a greater final value of 38.9 ± 3.6.

From this, we deduce that the noise of type 2 produces a greater influence on subjects A performance than noise of type 1, both referring to the silent condition.

At this point, many other considerations and analysis can be done. For example, supposing to have a panel of 50 subjects tested we can get a total $IPER_{0,100}$ mean value for the noise of type1 and type 2 as $IPER_{0,100}$ is directly comparable between subjects and get for example that the second one has an influence on the performance of 35% greater than the first one.

It is also possible to create some homogenous groups of subjects, for example, considering one parameter at time and then to test the possibility of a correlation with variables associated to the subjects (e.g. age, iris colour, sex, nationality…).

Each output involved in the IPER index evaluations comes from measurements or other procedures that can be assimilated to measurements. For example, the answer to a questionnaire is a measure of a subjective sensation or opinion on a psychological scale and an operational output is a measure of the capability to perform a given task.

The three constituents of the *IPER* index are known with a given uncertainty, evaluated following the methodologies describes above.

It is important to evaluate the uncertainty of *IPER* in order to clearly understand weak points in the experiment setup (e.g. if the uncertainty of a component is too high respect to the others) or to give the correct interpretation to numerical values.

As clearly explained in the International Vocabulary of Metrology (VIM), every number in the uncertainty interval has the same probability to represent the true value that if considered unique is, in practice, unknowable. Every comparison of results or deductions considering values inside the uncertainty interval has poor physical meaning.

According to the European Accreditation (EA) guide [27], all the expanded uncertainty specified before considers a rectangular distribution and should be reduced to a normal distribution before starting the uncertainty evaluation.

The coefficient of sensibility c_i where i is the generic parameter in *IPER* is:

$$c_{RPH_r} = \frac{RPH_r - RPH_t}{\left(RPH_{max} - RPH_{min}\right)^2 \sqrt{\frac{\left(RPH_r - RPH_t\right)^2}{\left(RPH_{max} - RPH_{min}\right)^2} + \frac{\left(ROP_r - ROP_t\right)^2}{\left(ROP_{max} - ROP_{min}\right)^2} + \frac{\left(RPS_r - RPS_t\right)^2}{\left(RPS_{max} - RPS_{min}\right)^2}}}$$

$$c_{RPH_t} = -c_{RPH_r}$$

$$c_{ROP_r} = \frac{ROP_r - ROP_t}{\left(ROP_{max} - ROP_{min}\right)^2 \sqrt{\frac{\left(RPH_r - RPH_t\right)^2}{\left(RPH_{max} - RPH_{min}\right)^2} + \frac{\left(ROP_r - ROP_t\right)^2}{\left(ROP_{max} - ROP_{min}\right)^2} + \frac{\left(RPS_r - RPS_t\right)^2}{\left(RPS_{max} - RPS_{min}\right)^2}}}$$

$$c_{ROP_t} = -c_{ROP_r}$$

$$c_{RPS_r} = \frac{RPS_r - RPS_t}{\left(RPS_{max} - RPS_{min}\right)^2 \sqrt{\frac{\left(RPH_r - RPH_t\right)^2}{\left(RPH_{max} - RPH_{min}\right)^2} + \frac{\left(ROP_r - ROP_t\right)^2}{\left(ROP_{max} - ROP_{min}\right)^2} + \frac{\left(RPS_r - RPS_t\right)^2}{\left(RPS_{max} - RPS_{min}\right)^2}}}$$

$$c_{RPS_t} = -c_{RPS_r}$$

Similar formulas are used for the each component of the IPER index.

5. Conclusions

The field of 'classical' metrology (the one related exclusively to physical quantities) is still formally lacking all the concepts around soft metrology. As a matter of facts, this is still considered a newborn branch of research that need a robust methodological and theoretical architecture to be recognised.

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However, due to what said before and described in this chapter, the interest on this topic is growing significantly. This is demonstrated by the recent interest by the fact, for example, many international congresses on metrology are adding specific sessions dedicated to human perception, appearance and in general about the quantification of subjective aspects of human–world interaction. Moreover, the Committee in charge for the new revision of GUM is recently willing to include definitions and models concerning soft metrology.

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