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PHYSIOLOGY AND SENSORIAL BASED QUANTIFICATION OF HUMAN-OBJECT INTERACTION – THE QOSI MATRIX

Balters, Stephanie; Bisballe Jensen, Matilde; Steinert, Martin
Norwegian University of Science and Technology, Norway

Abstract

This paper addresses the need to quantify human-object interactions in order to get insights into the sensorial variables influencing the actual user-experiences in interaction and human centered design. The resulting framework is generally applicable and allows the exploration of more fundamental human-object interaction relationships, including better benchmarking and comparison of alternative design options and the development of controlled experimental setups. We approach the problem of capturing human-object interactions from a sensorial perspective. Based on the functioning of the five human sensory systems (visual, auditory, somatosensory, gustatory, and olfactory), we distil 21 quantifiable and measurable input dimensions, which may come into play when a person interacts with an object. The resulting Quantified Object Sensation Input (QOSI) matrix gives the possibility to very specifically and precisely quantify and describe any human-object interaction based on the sensorial information it delivers. The matrix allows comparing different human-object interactions in a standardized and generally applicable manner, even if the objects have fundamentally different properties.

Keywords: User centred design, user-experience, human-object interaction, human sensory system, object quantification

Contact:
Stephanie Balters
Norwegian University of Science and Technology
Engineering Design and Materials
Norway
stephanie.balters@ntnu.no

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1 INTRODUCTION INTO HUMAN-OBJECT INTERACTION

In the world of human-centered engineering design, user-experience is one of the key-factors that make rather similar products vary in popularity among users. Rather than simply designing objects, we are in fact designing interactions (Moggridge, 2007), i.e. human object relations that are complex, subjective and highly relevant for a successful 'marriage'. Classical examples are smartphones that nowadays have very similar technical properties and functionalities, but still differ widely in terms of user attraction. Despite the growing acknowledgement in the field, user-experience is still a floating concept with blurry lines. Such ambiguity stems from an emerging community of practitioners with diverse backgrounds, to whom user-experience encompasses vast interpretations (Law, 2011). The international standard on ergonomics of human system interaction, ISO 9241-210, defines user-experience as 'a person's perceptions and responses that result from the use or anticipated use of a product, system or service'. According to the ISO definition, user-experience includes all the users' emotions, beliefs, preferences, perceptions, physical and psychological responses, behaviors and accomplishments that occur before, during and after use (ISO, 2010). Several papers have already tried to quantify and measure user-experience in different ways, however, as Law (2011) concludes: '*UX [user experience] as a phenomenon remains quite a mystery to unravel.'*

This paper aims to address the lack of measurability of user-experience from a different perspective, namely by proposing a tool for quantifying human-object interaction based on sensorial information. To narrow the broad field of user-experience, we will exclusively focus on the sensorial based 'experience' dimension of human-object interaction. Our human-centered approach is solidly grounded on findings in neuroscience, explaining how humans sense objects while interacting with the latter. The understanding of the human sensory system allows us to define object-user interaction from a plain physiological dimension. How can we describe an object from a purely physiological point of view? We define the '***human-object interaction'*** in order to capture the distinct dimensions of the user-experience. Generally, we address the following: (1) *humans* including engineering designer and users, (2) all physical *objects* within the product development process from early stage prototypes to final products and (3) *interaction* with these objects at any stage.

The first objective of this paper is to provide the community with the basic knowledge about the physiological mechanisms of the human sensory system. The reader will understand 'how we humans sense an object' by means of our five major sensory systems. The second objective is to construct a 'Quantified Object Sensation Input' matrix, which allows the designer/engineer to very specifically and precisely quantify human-object interaction in an easy and intuitive, yet standardized scientific and measurable way.

2 THE HUMAN SENSORY SYSTEM - OUR FIVE MAJOR SENSES

Vision, hearing, somatic sensation (touch), gustation (taste), and olfaction (smell) - the five major senses of the human body. They are solely as well as collective functioning and allows us the ultimate ability to perceive our environments. Even though these five sensations are very different in nature, they combine some common basic rules. They all change an external stimulus into an electrical impulse, which is processed to and interpreted by the brain. Impulses from the environment (e.g. light, tone, touch) are detected from its corresponding sensory receptor in the body surface (e.g. in the eye, in the ear, in the fingertip) and converted into an electrical nerve impulse (transduction). When an impulse stimulates its corresponding sensory receptor cell, ion channels in the cell membrane open, causing an influx of ions, depolarizing the cell. The resulting receptor potential (change in voltage across the receptor cell membrane) travels further on as action potential throughout the neuronal pathway to the brain (Purves, 2012; Tortora & Grabowski, 2003; Benarroch, 2006; Møller, 2003). This impulse includes information about quality and quantity as well as the location of a stimulus (Purves, 2012). Via the afferent pathway, these sensory signals are sent to the brain for processing. First processing station within the brain is the thalamus, which is situated deeply in the brain between brainstem and cerebral hemisphere (Bear et al., 2007; Conn, 2008). The thalamus acts as relay station and conveys sensory input to its target in the cerebral cortex. An exception is the olfactory system, which bypasses the thalamus and reaches directly its cortical target. Within this task, the thalamus functions as regulator of sensory information, since it decides which information are as important to be send to the cortex, where they reach our conscious awareness. Because of this 'grading of importance' and 'prioritizing one signal before the other' ability, the thalamus is commonly entitled as 'gateway to the brain' (Angevine and Cotman, 1981; Hendelman, 2005). The sensory stimuli are finally transferred to the cortex - the outer layer of the brain, also named grey matter, which surrounds each hemisphere. Here each sensation has its own specific processing area (Figure 1) (Mason, 2011; Møller, 2003). Note that it is not before reaching the primary cortices that the sensations are finally actively perceived and further integrated into the perception of 'one sensation'. Before this point the sensations are "just" electric current flows.

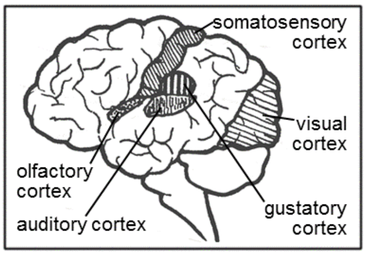

Figure 1. The primary sensory cortices

Light is reflected off an object, enters the **VISUAL SENSORY SYSTEM** through the cornea in the eye and is focused onto the retina via the adjustable lens (Purves, 2012; Haines, 2013; Galizia and Lledo, 2013). In the retina are two sorts of photoreceptors situated, (1) rods, which are very sensitive to light and facilitate 'black and white' vision and (2) cones, which enable vision of color and fine detail. Rods and cones transmit their inputs further to ganglion cells, where these impulses are transformed into electrical signals. There are two major types of ganglion cells, parvocellular and magnocellular cells. The former are most prevalent (ca. 80%) and receive their information from the cones. As consequence, they have high spatial resolution (see all little detail), very high color sensitivity and low temporal resolution (motion). Magnocellular cells in contrast, proceed stimuli from the rods and have characteristically a low spatial resolution as well as low color sensitivity, but high temporal resolution (Krebs, 2011; Spillmann and Werner, 2012). The electrical signals from both ganglion cell types are respectively sent on the magno and parvo pathway via the optic nerve and optic tract to the lateral geniculate nucleus (LGN), the primary visual relay station in the thalamus (Figure 2, left). The LGN conveys its processed and filtered information through the optic radiation to the visual cortex V1 in the back of the head - still separated into magno and parvo pathway. Within this cortical area, the signal is divided into a dorsal stream ('how pathway') and the ventral stream ('what pathway') (Nelson and Luciana, 2001; Baars and Gage, 2010). The dorsal stream, containing information about motion and depth of an object, travels via the visual cortex V2 and visual area MT to the posterior parietal cortex. This area is associated with motion and object location. The ventral stream, on the other side, includes information about form, color and detail of on object. It travels via the visual cortex V2 and visual cortex V4 to the inferior temporal lobe, which is involved in storage of long-term memory and the ability of recognition. Important to note is, that the left brain hemisphere receives stimuli from the right visual field and vice versa. These two signals are each processed within their own hemispheric side, meaning, the pathways described above, strides through on both sides of the brain (Figure 2, right). The visual sensory system distinguishes, thus, between form, color, detail as well as motion and depth of an object.

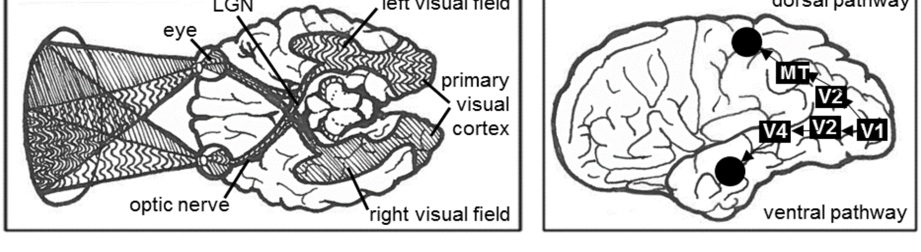

Figure 2. The visual sensory system

The **AUDITORY SENSORY SYSTEM** changes sound waves in the air into electrical impulses, which can be further interpreted by the brain. Sound waves reach the external ear and run through the external auditory canal until they encounter the tympanic membrane (eardrum) (Bear et al., 2007) Gazzaniga, 2004; Nelson and Luciana, 2001). This membrane vibrates forth and back in response to the frequency of the hitting sound waves. Sounds with lower frequency (pitch) produce slower vibrations while higher pitched sounds stimulate faster vibration. The sound volume influences, moreover, the intensity of the vibration: sounds with lower volume create a less vigorous vibration and vice versa. The oscillation of the tympanic membrane stimulates the mechanically connected 'three bone structure', consisting of maleus, incus, and stapes. Their resulting oscillating movement induces frequency impulses via the membranic over window of the 'snail shell like' cochlear (Figure 3, left). The cochlear is filled with a fluid, which vibrates in response to incoming impulses. First then, the vestibular canal within the cochlear sends incoming vibrations up into the apex area, while descending portions run down via the tympanic canal. A third structure, called cochlear duct, is situated between these two areas. When impulses travel through the vestibular canal, they are transferred to the cochlear duct via the flexible reissner's membrane (Bear et al., 2007; Nieuwenhuys et al., 2007; Sherwood, 2011). From the cochlear duct the signal travels via the flexible basilar membrane onwards to the tympanic canal, from where it descends back, out of the cochlear. The basilar membrane carries an important structure, called organ of corti (Figure 3, right). When the basilar membrane vibrates, the organ of corti is stimulated and generates a receptor signal, which is send to the brain. Importantly, the basilar membrane is significantly thinner at its beginning as at its end in the apex. Due to this structure, the entering vibration causes different sections of the basilar membrane to vibrate, depending on the corresponding frequency (since thinner part is easier to move). With low frequency (min. 20 Hz) the basilar membrane vibrates at its upper part close to apex, while high frequencies (max. 20.000 Hz) strike the basilar membrane in its lower part (Hamid and Sismanis, 2011). As the basilar membrane along with it the organ of corti vibrates up and down, cilia (fine hairs) on top of the organ of corti are bend by touching the upper tectorial membrane. This creates a cilia receptor potential, which is forwarded via the cochlear nerve to the primary audio cortex in the brain (one in each hemisphere), where the signals are processed. The auditory sensory system, thus, can differentiate between frequencies within a range from 20 Hz to 20000 Hz as well as the amplitude (volume) of the related frequency.

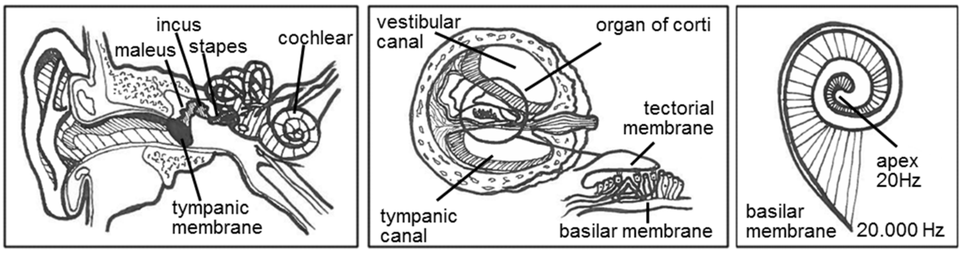

Figure 3. The auditory sensory system

The **SOMATIC SENSORY SYSTEM** originates within the dermis layer of the skin. Several types of sensory receptors facilitates tactile sensation (touch, pressure, and vibration), proprioceptive sensation (limb position) as well as sensation about nociception and temperature (pain, heat, cold) (Rhoades and Bell, 2012; Purves, 2012; Young et al., 2008). So-called mechanoreceptors are specialized cells to receive tactile information in the skin. In case receptor endings are mechanically deformed by touch, pressure or vibration, they generate a receptor potential by altering the permeability of cation channels, causing a depolarization. Generally, mechanoreceptors have a low threshold, are therefore easily excitable and, thus, very sensitive to a stimulus. Besides, they are either only firing at the beginning of a stimulus (rapidly adapting) or they fire continuously throughout the stimulus (slowly adapting). Depending on the receptor, there is a large difference in the receptive field as well as sort of excitable stimuli and corresponding detection function (Haines, 2013; Goldstein, 2008; Purves, 2012). In the fingertip, merkel cells are slowly adapting receptor cells in high skin layer with the highest spatial resolution, able to sense spatial details of only 0.5 mm. Merkel cells react to touch and light pressure. Moreover, they are highly sensitive to points, edges and curvature and are responsible for the sensation of form and texture. Meissner's corpuscles are also found in high skin layer, but of rapidly adapting nature with a spatial resolution of about 3mm. This type of mechanoreceptor is sensitive to moving stimuli as well as skin motion and is therefore responsible for motion detection and grip control. Ruffini endings are slowly adapting receptors in deep skin layer. Their spatial resolution is 7mm and they are responsible for the accurate representation of finger position and movement by detecting stretch in skin. Last, pacinian corpuscle are rapidly adapting receptors in the deep skin. Their resolution is 10mm and they are stimulated by external vibration and primary responsible for detecting surface texture (e.g. rough and smooth).

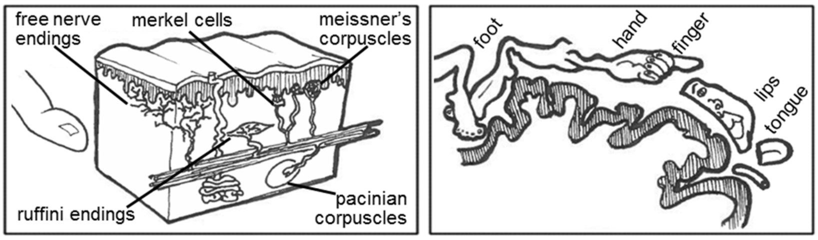

Figure 4. The somatosensory system

Free nerve endings are responsible for the sensation of pain and temperature. Nociceptors are found throughout the body tissue and react to intense thermal, mechanical or chemical stimuli by the release of chemicals (in case of tissue irritation or injury) (Tortora and Grabowski, 2003). Thermoreceptors are likewise free nerve endings and detect each a receptive field of approximately 1 mm in diameter. Thermoreceptors mediate different temperature ranges (there exist cold and warm thermoreceptors) and encode the temperature difference rather than the absolute temperature (think of cold hands and lukewarm water) (Bear et al., 2007; Sircar, 2008). Generally, the bigger the nerve is, the faster the signal travels. Since mechanoreceptors are bigger than free nerve endings, they convey impulses much faster (think of touching the hot stove with your hand – you feel the touch faster than temperature and pain). Sensory cells convey the signal via the spinal cord to the brain, where they pass the ventro-posterior nucleus (VPN) of the thalamus and finally reach the primary somatosensory cortex in the brain. The primary somatosensory cortex is a slide of cortex (see Figure 4, left) in which every portion codes for a specific body area (Purves, 2012; Schünke et al. 2007). Body parts, which are most sensitive (like lips and fingers) have the most amount of receptors within its body area and, moreover, in proportion space in the primary somatosensory cortex. The somatosensory system (in particular of fingertips) allows the ability to perceive and recognize the form of objects in the absence of visual and auditory information, by using tactile information to provide cues from texture, size, spatial properties, temperature, pain, finger position, and finger slippage.

The **GUSTATORY SENSORY SYSTEM** allows the detection of chemical substances in the mouth in classification of salty, sweet, bitter, sour, and umami (savory flavor) (Goldstein, 2010; Chen and Engelen, 2012). Primary taste organ are taste buds, located at the bottom of tissue folds (called papilla) all over the tongue (see Figure 5). Taste buds consist of gustatory cells and supporting cells, which surround the former. Microscopic food molecules enter these folds, reaching gustatory cilia (fine hairs) on one end of the gustatory cell. These hairs carry chemoreceptors, which sense the presence of their corresponding chemical molecule. In this manner, the taste of salt is caused by the presence of sodium (Na^+) and chlorine (Cl^-) ions within the tissue folds, whereas sour taste results from hydrogen chloride (HCl) and citric acids molecules (both prevalent in acids). Sugars, such as glucose and sucrose, code for sweet taste and quinine sulphate for bitter flavor. Last, amino acids (glutamate and proteins) facilitate the sensation of umami (Galizia and Lledo, 2013; Brady et al., 2011). Hence, the sensation of different tastes is accomplished by different chemo-receptors and their corresponding microscopic food molecule on the cilia membrane of every taste cell. A different intensity concentration of each receptor throughout the tongue results in a different sensitivity of taste sensations in different areas of the tongue (Figure 5). In first place, a prevalence of receptors for sweet taste is found in the tip of the tongue. Salty taste is mostly detectable through the rim of the tongue, along with sour taste sensation at the sides and bitter flavor detection in the back of the tongue. At last, umami dependent receptors are distributed all throughout the tongue (Purves, 2012). Even though the majority of taste receptors is found directly on the tongue, some others are scattered within the throat, pharynx, and epiglottis (Bear et al., 2007; Johnson, 2003; Carter, 2014). When a food molecule bines to its receptor on the cilia, the corresponding gustatory sensory cell generates a receptor potential and sends this electrical signal via cranial nerve fibers (facial, glossopharyngeal, vagus nerve) to the brain. Stimuli from the anterior part of the tongue run through the facial nerve, those from the posterior part via the glossopharyngeal nerve and, last, signals from scattered taste buds in throat, pharynx, and epiglottis throughout the vagus nerve to the brain. All three pathways synapse within the medulla oblongata (within the brainstem) and proceed throughout the ventral posterior medial nucleus of the thalamus to its target - the primary gustatory cortex in the ventral parietal lobe (Bear et al., 2007; Augustine, 2008).

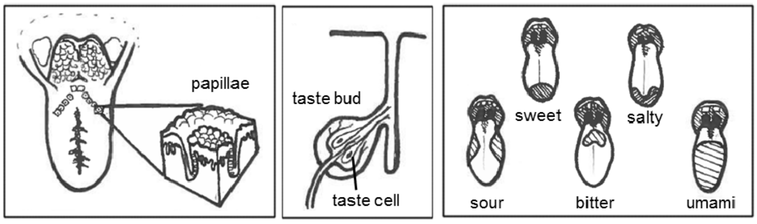

Figure 5. The gustatory sensory system

As air passes through the nasal cavity, entering the **OLFACTORY SENSORY SYSTEM**, it carries odorants in it. These molecules reach the olfactory epithelium, which lines the superior part of the nasal cavity and is protected by a mucus layer, allowing the odorants to dissolve. The epithelium contains three major parts, (1) olfactory receptor cells with cilia at its end, spreading throughout the mucus layer; (2) supporting cells, creating a scaffold structure around the latter as well as (3) bowman's glands, which produce the essential mucus (Hawkes and Doty, 2009; Johnson and Byrne, 2003). In the same way as in the gustatory system, dissolved odorants bind to their respective receptor on the fine hairs of olfactory cells and activate these. The generated receptor potentials are carried via the olfactory nerve into the olfactory bulb that lies within the cranial cavity just underneath the frontal lobe of the brain. There are approximately about 200 different odorant receptors present within the human mucus layer - each able to detect a small number of related molecules - coding for estimated 10,000 different odors (Buck and Axel, 1991; Purves, 2012; Longstaff, 2005). All axons of one specific receptor synapse within one specific 'receptor dependent area' (called glomerulus) within the olfactory bulb. From each glomerulus, the signal is then projected to the primary olfactory cortex in the temporal lobe via the olfactory tract. The primary olfactory cortex conveys the signal to (1) the secondary olfactory cortex (olfactory association area); (2) to the mediodorsal area of the thalamus (is associated with memory function) and (3) to the limbic system (emotional response) (Binder and Sonne, 2011; Nieuwenhuys et al., 2007).

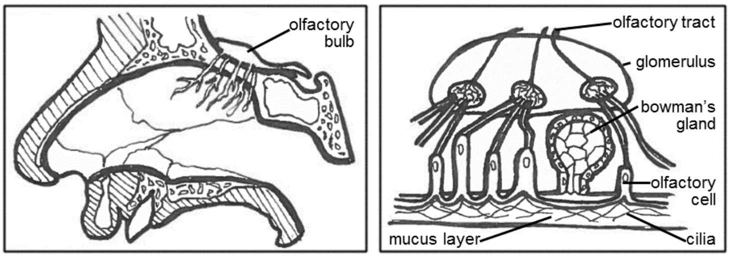

Figure 6. The olfactory sensory system

Odorants can also be released by food particles in the mouth. These microscopic molecules enter the nasal cavity via the back of the throat. Since the gustatory system can only detect five distinct flavor sensations, the olfactory sensory system supports our sensation of 'eating and drinking' in a great extent. Whenever the nasal cavity is congested due to a cold or allergy, odorant molecules can no longer reach the receptor cells and we can no longer smell (Calvert and DeVere, 2010) (this is also the case if you hold your nose closed).

3 INTRODUCING THE QUANTIFIED OBJECT SENSATION INPUT MATRIX

The previous section presented the physiological functioning of the major five sensory systems of the human body. Their common principle is the collection of external signals via their respective sensory

system entry points within the body surface. Different sorts of receptor cells collect different sorts of signals, which are transduced into electrical impulses and sent via afferent pathways to the brain for further processing. The functioning of each receptor cell defines, thus, the external signals (object information) entering the somatic system. Only those object information that enter the human system, are accessible for the subsequent reconstruction of the object within the cortex of the brain. In other words, the 'mentally reconstructed object' is based on and limited to those information stimuli, which are filtered and passed through the sensory system gateways. We therefore propose to use a combination of filtered object information to describe a design object in a holistic and yet objective manner. It is important to note, that (1) we focus solely on the distilled information of the considered design object placed in a static and constant surrounding setting (2) we focus solely on the raw sensory data information excluding any further cognitive and/or conscious processing, such as integration of memory, emotional state or individual preferences.
For each sensory system, we collected, firstly, the object properties (such as form, color, motion), which are detected and filtered by the corresponding system receptors. Secondly, we assigned each of these parameters with a physical quantity. Thirdly, we identified a physical or chemical measurement technique for each parameter. Lastly, we summarized the results into one single reference – the Quantified Object Sensation Input (QOSI) matrix. We propose to use this matrix to describe, measure, and quantify objects in engineering design. Table 1 provides an overview of the identified quantified object parameters – 21 in total – of which the characteristics and underlying measurement technique will be further explained. By means of illustration, we encourage the reader to place Object A (e.g. your coffee cup) in front of you, defining the center of this exact placement as zero point position P_0 (x_0, y_0, z_0).

Table 1. Quantified Object Sensation Input (QOSI)

	**LIGHT INTENSITY** illuminance $[lx]$	**COLOR** amount of colors $[\#]$ wavelength $[nm]$	**MOTION** velocity vector $\begin{bmatrix} m/s \\ m/s \\ m/s \end{bmatrix}$	**DEPTH** meter $\begin{bmatrix} m \\ m \\ m \end{bmatrix}$	**FORM** volume $[m^3]$	
	**(TONE) FREQUENCY** frequency $[Hz]$	**VOLUME** sound pressure level $[dB]$				
	**TOUCH PRESSURE** force/ area $\left[\frac{N}{m^2}\right]$	**OBJECT MOVEMENT** velocity vector $\begin{bmatrix} m/s \\ m/s \\ m/s \end{bmatrix}$	**FINGER MOVEMENT** velocity vector $\begin{bmatrix} m/s \\ m/s \\ m/s \end{bmatrix}$	**TEMPERATURE** abs. temperature $[K]$ thermal conductivity $[W/mK]$	**VIBRATION** frequency $[Hz]$ amplitude $[m]$	**SURFACE TEXTURE** lay $[a - e]$ roughness $[Ra]$
	**SALTY IONS** molar concentration $\left[\frac{mol}{L}\right]$	**SOUR IONS** molar concentration $\left[\frac{mol}{L}\right]$	**SWEET IONS** molar concentration $\left[\frac{mol}{L}\right]$	**BITTER IONS** molar concentration $\left[\frac{mol}{L}\right]$	**UMAMI IONS** molar concentration $\left[\frac{mol}{L}\right]$	
	**CONCENTRA-TION** odor units/ volume $\left[\frac{OU}{m^3}\right]$	**INTENSITY** odor intensity $[0 - 6]$	**HEDONIC TONE** $[0 - 6]$			

The receptors of the **VISUAL SENSORY SYSTEM** in the eyes allow humans to recognize the following five dimensions: light intensity, color, motion as well as depth and form of Object A. *Light intensity* is described by the physical quantity 'illuminance', which is defined as the sensed (light) power per defined area at a specific position P_0 (which we set just on top of cornea in the center of pupil diameter of the right eye). Illuminance can be measured with lux meters and are specified in [lm/m^2= lx] (Lindsey, 1997). The definition of illuminance comprises the consideration of distance-dependent light intensity to the light source (light reflecting object). When it comes to objects, the characteristics of the material in use, concerning for example reflection, absorption, and transfer of light properties, affect the shininess of a material and thus its ability to reflect light. *Color* is measured by the use of spectrometers that capture the wavelength in [nm] of the respective color spectrum (Avison, 1989). The visual color spectrum of the human sight spans from 300nm to 700nm (DeWolf et al., 1974). The color experience of the human-object interaction will be characterized by firstly, the amount of object colors [#] and secondly, by their respective wavelength. *Motion* of Object A detected by the visual sensory system, can be captured by a 3D accelerometer and described by the motion's velocity vector [m/s; m/s; m/s], which includes by definition speed and direction of the movement. Depth and form of Object A are closely linked to each other and yet, due to their complexity, challenging to describe as single values. As starting point, we suggest to meter the longest extent of Object A in x, y, z plane and to indicate each *depth* in meter [m; m; m]. Moreover, we suggest to quantify *form* based on its volume [m^3]. To describe the shape of Object A in a more detailed and elaborated way, one needs advanced mathematical methods (such as finite element method), which yet do not allow to express through one distinct unit. The emerging technology of 3D scanning might help in the future to scale 'form' in a more comparable way.

The **AUDITORY SENSORY SYSTEM** detects frequency and volume of a sound wave. Firstly, *frequency* is specified in hertz (Hz) and can be calculated by Fast-Fourier-Transformation of a (with a microphone captured) tone (Noble, 2009). Its perceptibility through the human ear ranges between 20 and 20.000 Hz (Rossing, 2007). Certain ground frequencies represent different tones such as the middle C tone on a standard piano with a frequency of 261,6 Hz (Rossing, 2007). Secondly, sound pressure quantifies the *volume* of a tone in the unit decibel (dB) and can be measured with a sound level meter (Ballou, 2013). The human pain threshold of sound pressure varies around 125 dB, while the ear drum will burst being exposed to decibel values of approximately 180 dB (Rossing, 2007). We divide the human-object sensation 'sound' into two subunits: On the one hand, it is the actual sound (as combination of frequency and sound pressure) an object makes in usage, such as the sound of closing a car door, running a diesel engine or the feedback sounds in user-object interfaces. On the other hand, we consider the sound made by the interaction with the object (Velasco et al., 2014). In order to explain and compare the sound experience of objects, we suggest to measure the resulting 'interaction sound' (as combination of frequency and sound pressure) due to 'knocking' with the fingertip onto the material with a constant force F_F and constant velocity v_F.

The **SOMATIC SENSORY SYSTEM**, within this context limited to the fingertip of the right index finger, is able to detect touch pressure, object movement, finger movement, temperature, vibration, and surface texture. Force (captured by capacitive sensors) per area (is to be metered) defines *touch pressure* [N/m^2]. This definition allows the differentiation between two interaction cases: first, area A1 of Object A is pushed with force F1 onto the fingertip or second, the fingertip is pushed onto Object A with force F2 and contact area A2. *Object movement* implies the ability to sense the motion of contact area A3 of Object A from position P_{O0} (x_{O0}, y_{O0}, z_{O0}) to the end position within the fingertip. It is quantified by its velocity vector [m/s; m/s; m/s] and contains, thus, the speed and direction of the movement. *Finger movement*, on the contrary, contains the ability to perceive the finger position and further the ability to 'measure' object dimensions via palpation with the fingertip, for example illustratively in case of being blindfolded. We define the exact center of the fingertip as starting position P_{F0} (x_{F0}, y_{F0}, z_{F0}) and describe the movement with its velocity vector [m/s; m/s; m/s] as combination of direction and speed. Both movements can be captured via 3D accelerometers. When interacting with an object, the material has great saying in the experience of *temperature*. Metal is exemplarily known to feel colder than wood, despite having the same (absolute) temperature. This phenomenon results due to different thermal conductivity properties of the two materials (Obata, 2005). In this sense, temperature of Object A will be characterized by its absolute surface temperature in [K] as well as its material-dependent thermal conductivity value in [W/mK]. The absolute temperature is measureable with thermometers, whereas material-dependent thermal conductivity values can be found in scientific reference tables (Adler, 2007). *Vibration* of Object A can be sensed with the fingertip of the right index finger by lightly touching the object surface. We define vibration in this context as oscillation, described through its frequency [Hz] and amplitude [m]. 3D accelerometer can assist to measure the two vibration components. *Surface texture* is understood as the deviation from a perfect flat ideal surface by the combination of mainly (1) surface lay and (2) surface roughness (Anaheim and Adithan, 2007). Lay is the direction of the predominant surface pattern ordinarily determined by the production method used' (Anaheim and Adithan, 2007). Its variation will be scaled by the objective classification of the surface to be predominant: (a) vertical, (b) horizontal, (c) radial, (d) cross-hatched, (e) circular or (f) isotropic. Surface roughness is most commonly described with its one-dimensional arithmetic average of absolute values parameter Ra (Anaheim and Adithan, 2007). Ra is calculated based on the amount of microscopic peaks and valleys of the examined surface.

The receptors of the **GUSTATORY SENSORY SYSTEM** define what humans are able to taste. All external (food) molecules can either be sub-sorted into salt, sour, sweet, bitter, or umami, or not (sensory) sensed at all. The detection of prevalent molecules demands chemical experiments based on for example swipe samples from the surface of tongue and analysis via mass-spectrography to measure the concentration of each of the specific taste molecules in [mol/ L] (Gross, 2004). *Salty* taste is quantified by the concentration level of sodium [Na^+] and chlorine ions [Cl^-], *sour* taste by the concentration level of hydrogen ions [H^+], *sweet* taste by concentration level of sugars such as carbohydrates [$C_nH_{2n}O_n$], *bitter* taste commonly by the concentration level of quinine [$C_{20}H_{24}N_2O_2$] and *umami* by the concentration level of sodium glutamate [$C_5H_8NO_4Na$] (Buck, 2000). In human-object interaction experiences, the gustatory sensory system might be counterintuitive to include since we very seldom taste an object. However, for reasons of content completeness, the gustatory dimension needs to be considered.
The **OLFACTORY SENSORY SYSTEM** contains 200 different odorant receptors - each able to detect a small number of related molecules - coding for estimated 10000 different odors (Buck and Axel, 1991; Purves, 2012; Longstaff, 2005). Because of the large spectrum of the olfactory system, it remains very hard to ‘measure’ all the different olfactory molecules. Accepted measurement methods in olfaction science are both olfactormeters and trained olfaction experts. The measurement of smell contains therefore a mix of scientific units and verbal descriptions (Jiang et al., 2006; Davide et al., 2001). In olfactory science, smell is described in three categories: (1) *Concentration* measured by olfactormeters in odor units per volume [OU/m^3] as well as (2) *intensity* and (3) *hedonic tone,* which are both ranked by experts on a scale from 0-6 (Jiang et al., 2006). The study of odors is of extreme complexity. Some researchers even claim that smell is ‘more a feeling than an actual sensation’ (Yeshurun and Sobel, 2010). Since the olfactory sensory system bypasses the filtering system ‘thalamus’ in the brain and is moreover closely connected to the emotional center in the brain, the potential (hidden) effects of olfaction on human-object interaction experience should not be overlooked.

4 FUTURE APPLICATIONS OF THE QOSI MATRIX

In this paper, we approached the problem of capturing human-object interactions from a purely physiological perspective, based exclusively on the sensorial data input. The functioning of each receptor cell within the human sensory systems determines which external signals (object information) enter the somatic system. Only those object information that enter the human system, are accessible for the subsequent reconstruction of the object within the cortex of the brain. We therefor proposed to describe a human-object interaction solely based on this bundle of raw sensory data (before cognitive processing!).
For each sensory system, we collected, firstly, the object properties, which are detected and filtered by the corresponding system receptor cells. Secondly, we assigned each of these parameters with a physical quantity. Thirdly, we identified a physical or chemical measurement technique for each parameter. Lastly, we summarized the results into one single reference – the Quantified Object Sensation Input (QOSI) matrix.
This QOSI matrix provides a single reference for gathering the critical information needed for engineering designers to better frame, and reflect upon the role of the five senses in a human-object interaction and the resulting user-experience. QOSI shall motivate to explore and expand the design of human-object interaction by exemplarily integrating product features stimulating or suppressing human sensation. Most notably, we propose the QOSI matrix as design tool to measure, scale, and quantify any human-object interaction. This we believe to be of crucial importance in the world of user-experience and interaction design, since it provides the community for the first time with a standardized and factual technique for not only quantifying but also comparing human-object interactions – even if the objects have fundamentally different properties.
Practically, such a comparison is deemed valuable during the entire product development process as it allows comparing the interaction with different prototypes, tools, and end products across time and object groups. Hence, QOSI can support identifying and categorizing user-group-dependent preferences of interaction parameters with the aim to design customized product and system concepts. Scientifically, the community will be enabled to quantify the sensorial part of the human-object interactions in an objective, generally applicable, reproducible, and comparable way for examining the

impact of changes within the human-object interaction design onto the experience of the user. It is crucial to identify and define the independent variables in order to understand the underlying mechanisms of the complex and hitherto evasive dependent variable 'subjective user-experience'. We see QOSI as an initial point of detecting those influencing variables by introducing a quantified approach to the broad concept of user-experience-design. In Bisballe Jensen et al. (2015) we provide a study of applying QOSI when describing and evaluating prototypes used throughout a product development process. A further experimental validation study is currently being conducted, which will test QOSI in various possible application cases and deduce its potentials and limitations.

REFERENCES

Adler, D. (2007) Metric Handbook. Routledge.

Anaheim, C.A., Adithan, M. (2007) IEEE/CHMT International Electronic Manufacturing Technology Symposium. Manufacturing Technology. New Age International.

Angevine, J.B., Cotman, C.W. (1981) Principles of Neuroanatomy. Oxford University Press.

Augustine, J.R. (2008) Human Neuroanatomy. Academic Press.

Avison, J. (1989) The World of Physics. Nelson Thornes.

Baars, B.J., Gage, N.M. (2010) Cognition, Brain, and Consciousness: Introduction to Cognitive Neuroscience. Academic Press.

Ballou, G. (2013) Handbook for Sound Engineers. Taylor & Francis.

Bear, M.F., Connors, B.W. Paradiso, M.A. (2007) Neuroscience. Lippincott Williams & Wilkins.

Benarroch, E.E. (2006) Basic Neurosciences with Clinical Applications. Elsevier Health Sciences.

Binder, D.K., Sonne, D.C. (2011) Cranial Nerves: Anatomy, Pathology, Imaging: Anatomy, Pathology, Imaging. Thieme.

Brady, S., Siegel, G., Albers, R.W. Price, D. (2011) Basic Neurochemistry: Principles of Molecular, Cellular, and Medical Neurobiology. Academic Press.

Buck, L., Axel, R. (1991) A Novel Multigene Family May Encode Odorant Receptors: A Molecular Basis for Odor Recognition. Cell 65 (1): 175–87.

Buck, L.B. (2000) Smell and Taste: The Chemical Senses. Principles of Neural Science - Smell and Taste 4: 625–47.

Calvert, M., DeVere, R. (2010) Navigating Smell and Taste Disorders. Demos Medical Publishing.

Carter, R. (2014) The Brain Book. Dorling Kindersley Ltd.

Chen, J., Engelen, L. (2012) Food Oral Processing: Fundamentals of Eating and Sensory Perception. John Wiley & Sons.

Conn, M. (2008) Neuroscience in Medicine. Springer Science & Business Media.

Davide, F., Holmberg, M., Lundström, I. (2001) Virtual Olfactory Interfaces: Electronic Noses and Olfactory Displays. Communications through Virtual Technology: Identity Community and Technology in the Internet Age.

DeWolf, D.A, DiStasio, A.J., Doyle, T., Faulkner, R.D. (1974) RCA Electro-Optics Handbook. Rca.

Galizia, G., Lledo, P.-M. (2013) Neurosciences - From Molecule to Behavior: A University Textbook. Springer Science & Business Media.

Gazzaniga, M.S. (2004) The Cognitive Neurosciences. MIT Press.

Goldstein, E.B. (2008) The Blackwell Handbook of Sensation and Perception. John Wiley & Sons.

Goldstein, E.B. (2010) Encyclopedia of Perception. SAGE.

Gross, J.H. (2004) Mass Spectrometry: A Textbook. Springer Science & Business Media.

Haines, D.E. (2013) Fundamental Neuroscience for Basic and Clinical Applications,with Student Consult Online Access,4: Fundamental Neuroscience for Basic and Clinical Applications. Elsevier Health Sciences.

Hamid, M., Sismanis, A. (2011) Medical Otology and Neurotology: A Clinical Guide to Auditory and Vestibular Disorders. Thieme.

Hawkes, C.H., Doty, R.L. (2009) The Neurology of Olfaction. Cambridge University Press.

Hendelman, W.M.D. (2005) Atlas of Functional Neuroanatomy, Second Edition. CRC Press.

ISO. (2010) 'ISO 9241-210:2010 Ergonomics of Human-System Interaction -- Part 210: Human-Centred Design for Interactive Systems'. International Organization for Standardization.

Jiang, J., Coffey, P., Toohey, B. (2006) Improvement of Odor Intensity Measurement Using Dynamic Olfactometry. Journal of the Air & Waste Management Association 56 (5): 675–83. doi:10.1080/10473289.2006.10464474.

Johnson, L.R. (2003) Essential Medical Physiology. Academic Press.

Johnson, L.R., Byrne, J.H. (2003) Essential Medical Physiology. Academic Press.

Krebs, C. (2011) Neuroscience. Lippincott Williams & Wilkins.

Law, E.L.C. (2011) The Measurability and Predictability of User Experience. Proceedings of the 3rd ACM SIGCHI, 1–9.
Lindsey, J.L. (1997) Applied Illumination Engineering. The Fairmont Press, Inc.
Longstaff, A. (2005) Neuroscience. Garland Science.
Mason, P. (2011) Medical Neurobiology. Oxford University Press.
Moggridge, B. (2007) Designing Interactions. Cambridge, Mass.: MIT Press.
Møller, A.R. (2003) Sensory Systems: Anatomy and Physiology. Gulf Professional Publishing.
Nelson, C.A., Luciana, M. (2001) Handbook of Developmental Cognitive Neuroscience. MIT Press.
Nieuwenhuys, R., Voogd, J., van Huijzen, C. (2007) The Human Central Nervous System: A Synopsis and Atlas. Springer Science & Business Media.
Noble, J. (2009) Programming Interactivity: A Designer's Guide to Processing, Arduino, and Openframeworks. O'Reilly Media, Inc.
Obata, Y. (2005) Research on Better Use of Wood for Sustainable Development: Quantitative Evaluation of Good Tactile Warmth of Wood. Energy 30 (8): 1317–28. doi:10.1016/j.energy.2004.02.001.
Purves, D. (2012) Neuroscience. Sinauer Associates.
Rhoades, R.A., Bell, D.R. (2012) Medical Phisiology: Principles for Clinical Medicine. Lippincott Williams & Wilkins.
Rossing, T. (2007) Handbook of Acoustics. Springer.
Schünke, M., Schulte, E., Schumacher, U. (2007) Thieme Atlas of Anatomy: Head and Neuroanatomy. Thieme.
Sherwood, L. (2011) Fundamentals of Human Physiology. Cengage Learning.
Sircar, S. (2008) Principles of Medical Physiology. Thieme.
Spillmann, L., Werner, J.S. (2012) Visual Perception: The Neurophysiological Foundations. Elsevier.
Tortora, G.J., Reynolds Grabowski, S. (2003) Principles of Anatomy and Physiology. New York: Wiley.
Velasco, C., Salgado-Montejo, A., Marmolejo-Ramos, F., Spence, C. (2014) Predictive Packaging Design: Tasting Shapes, Typefaces, Names, and Sounds. Food Quality and Preference 34 (June): 88–95. doi:10.1016/j.foodqual.2013.12.005.
Yeshurun, Y., Sobel, N. (2010) An Odor Is Not Worth a Thousand Words: From Multidimensional Odors to Unidimensional Odor Objects. Annual Review of Psychology 61 (1): 219–41. doi:10.1146/annurev.psych.60.110707.163639.
Young, P.A., Young, P.H., Lee Tolbert, D. (2008) Basic Clinical Neuroscience. Lippincott Williams & Wilkins.

UNITS

dB	decibel
Hz	Hertz
K	Kelvin
L	Liter
lx	Lux
m	Meter
mol	Mol
N	Newton
nm	Nanometer
OU	Odor unit
s	Second
W	Watt

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