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The Stevens law and the derivation of sensory perception

Jianshe Chen[a,*], Shiyi Tian[a], Xinmiao Wang[a], Yuezhong Mao[a], Lei Zhao[b]

[a] Institute of Food Oral Processing and Sensory Sciences, School of Food Science and Biotechnology, Zhejiang Gongshang University, Hangzhou, Zhejiang 310018, China

[b] Food and Agriculture Standardization Institute, China National Institute of Standardization, Beijing, China

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ABSTRACT

The Stevens law, $S = kI^n$, is commonly accepted as a landmark achievement in the field of sensory psychophysics and has been widely applied in food sensory research. The theory effectively links the two parameters of very different nature, the intensity of sensory perception (S) and the intensity of physical stimulus (I). However, the Stevens law suffers from two major drawbacks. The equation was self-inconsistent in terms of the units, which makes equation questionable in principle. The Stevens law was also found inapplicable when multiple physical stimuli are involved in the perception of a sensory attribute. To solve the first drawback, we propose to replace the absolute stimulation intensity in the Stevens law with a relative intensity, $S = k(I/I_0)^n$. The modified Stevens law becomes self-consistent when both sides of the equation are dimensionless and the theory is applicable regardless of the unit of the physical stimulus. To solve the second drawback, a concept of sensory derivation is introduced and so sensory properties can be categorized as primary sensory and derived sensory. The former can be described effectively by the Stevens law, while description of the latter is beyond the applicability of the Stevens law because of the involvement of multiple sensory stimuli or multi level sensory derivation. Furthermore, a sensory hierarch is constructed with sensory perception of different nature at different levels, including the primary sensory at the basic level and derived sensory perception at progressing levels. The modified Stevens law provides a self-consistent model for psychophysical analysis of sensory perception. The proposed sensory hierarchy helps to streamline sensory terms and attributes and may be used as a useful guide in establishing instrumental analysis of sensory perception.

1. Introduction

Sensory perception is a process through which human beings interact with and perceive physical stimuli of an external object. The conversion of the perceived stimulus information into sensory perception is a hugely complicated internal process which remains somewhat mysterious and is still little understood. In the past decades, extensive studies have been conducted on the psychophysical principles of sensory perception, of which a main focus has been on the possible instrumental techniques for objective assessment of sensory attributes. Food industry is particularly keen in obtaining feasible techniques for quantitative sensory analysis, so that sensory properties of a food product and consumers' preference can be assessed and predicted by a precise objective measurement. A core challenge to instrumental sensory analysis is of course the relationship between a sensory attribute and its corresponding material stimulus. One of authors argued in a previous paper that, despite of the natural link between a sensory attribute and its corresponding material property, the two features are different in nature and, therefore, cautions need to be taken when using instrumental results for sensory interpretation [1]. An important reason is that sensory perception is largely derived through a very complicated internal psychophysical process and the controlling psychophysical mechanisms of the process are simply too complicated to be duplicated by an instrument.

* Corresponding author at: Institute of Food Oral Processing and Sensory Sciences, School of Food Science and Biotechnology, Zhejiang Gongshang University, Hangzhou, Zhejiang 310018, China.

E-mail address: jschen@zjgsu.edu.cn (J.S. Chen)

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The Stevens law, proposed more than six decades ago, has been widely seen as a plausible psychophysical model of sensory perception [2]. In a rather simple manner, the law makes a direct link between two features of completely different nature, human perception and material property. Despite the law has been widely welcomed and successfully tested for many cases, it suffers two major drawbacks. Firstly, the Stevens law was actually self inconsistent. Different results could be obtained if the physical stimulus is expressed in a different unit, making the equation questionable in principle. Secondly, the law is only applicable to those sensory features whose perception involves only a single physical stimulus, but the law becomes inapplicable once multiple stimuli get involved in the perception of a sensory attribute. In this paper, authors propose a modified dimensionless Stevens law and so make the theory applicable regardless of the units used for the physical stimulus. Concept of sensory derivation was also proposed in this work and authors argue that sensory features can be classified into multiple levels as a result of derivation. A sensory hierarchy is therefore constructed to give a full profile of sensory perception including the primary at the basic level and derived sensory at progressing levels. Primary sensory can be effectively governed by the Stevens law, but the governing laws for the derived sensory remain to be explored.

2. The limits of the Stevens law and its modifications

The psychophysical model published by Stevens more than six decades ago has been seen as a landmark achievement in the history of sensory science [2]. The Stevens law makes a direct connection in a rather simple manner between the two terms of completely different nature, the sensory attribute (human perception) and its corresponding physical stimulus (the material property). According to this theory, the intensity of a sensory attribute perceived by human can be expressed as a power-law function of the intensity of its corresponding physical stimulus,

$$S = \mathrm{k}I^{n} \tag{1}$$

where S represents the perceived intensity of a sensory attribute; I represents the intensity of the material stimulus, and n is the power law index. The applicability and reliability of the power-law equation has been proved by many studies, including the most convincing results obtained by Stevens himself [3], as shown in Table 1.

Implications of Stevens law were extensive both for fundamental understanding of the psychophysical mechanisms of sensory perception and for developing practical methodologies in sensory analysis. The value of the power law index, n, indicates the sensitivity of human perception to the change of the physical stimulus. As a very special case when the power law index n equals to 1, the human perceived sensory intensity will have a linear relationship with the intensity of the physical stimulus, which means that human beings have the same sensitivity as the designated physical instrument in assessing the intensity of the stimulus. However, in most cases, n was found to be either larger or smaller than unity, indicating that human's perception does not have a linear relationship with the intensity of its corresponding physical stimulus. A higher n value means much increased human sensitivity in perceiving the stimulus, whereas a value smaller than unit means a lower human sensitivity [4]. As shown in Table 1, very different n values, from as low as only 0.33 for brightness perception to as high as 3.5 for electric shock have been observed for different sensory attributes [3]. An n value of as low as 0.22 has also been observed for thickness perception against the objective viscosity measurement [5].

Table 1

Representative exponents of the power functions for various stimuli as obtained from the Stevens law [3]. A wide range of power law index, n, was obtained for various sensory features, reflecting very different sensitivity of human sensation of corresponding physical stimulus. The higher the n value, the more sensitive of human perception of such a feature. As claimed by the author, the exact value of n is difficult to determine with precision, and values listed here must be regarded as first approximations only. In all cases, the result was an average value for more than ten observers and is not necessarily appropriate to a particular individual.

Stimulus	Power law index (n)	Conditions
Loudness	0.6	Binaural
Loudness	0.55	Monaural
Brightness	0.33	5° target, dark-adapted eye
Brightness	0.5	Point source, dark-adapted eye
Smell	0.55	Coffee odour
Smell	0.5	Heptane
Taste	0.8	Saccharine
Taste	1.3	Sucrose
Taste	1.3	Salt
Pressure on palm	1.1	Static force on skin
Heaviness	1.45	Lifted weights
Force on handgrip	1.7	Precision hand dynamometer
Vocal effort	1.1	Sound pressure of vocalization
Electric shock	3.5	60 c.p.s. though fingers

Having taken into consideration of the existence of threshold values for various sensory attributes, various modifications have been made to the Stevens law. Equ (2) and (3) are two typical examples of modified Stevens law, the *effective threshold model* (Equ (2)) and the *physiological noise model* (Equ (3)) [6], in which I_0 is the threshold value, a critical value at which stimulation begins to be perceived (that is, $S = 0$, when $I = I_0$).

$$S = k\,(I - I_0)^{n} \tag{2}$$

$$S = k\,(I^{n} - I_0^{n}) \tag{3}$$

Despite of wide acceptance of the Stevens law and its modified versions, limits and contradictories still exist when applying this theory for practical sensory analysis [1]. One obvious drawback is the self-inconsistency of the units of the equation. The sensory attribute S on the left side of the equation is a psychology term with no defined dimension, but the physical stimulus on the right side of the equation refers to a material property and has to be expressed in an appropriate unit (for example, Newton for force, mole for concentration, Pascal for pressure, and etc) in order to be physically meaningful. Based on the Stevens law, the sensory perception will be dependent on the unit used for stimulus. This is of course against the principle of sensory perception.

To avoid this inconsistency, the authors believe that the physical stimulus intensity in Stevens law would be better expressed in relative term. The intensity ratio of the stimulus to its threshold value, I/I_0, should be used, as expressed in Equ (4). In this way, Stevens law becomes self-consistent when on both sides of the equation are dimensionless. The intensity of sensory perception will be a function of the relative intensity of the physical stimulus regardless of its dimensions.

$$S = \mathrm{k}\left(\frac{I}{I_0}\right)^n \quad (4)$$

The above equation can be conveniently converted as

$$\ln S = n\ln\left(\frac{I}{I_0}\right) + \ln\mathrm{k} \quad (5)$$

or

$$\ln S = n\ln I - n\ln I_0 + \ln\mathrm{k} = n\ln I + k' \quad (6)$$

where $k' = \ln\mathrm{k} - n\ln I_0$

From Equ (5), a plot of ln$S$ against ln(I/I_0) would give a straight line with its slope giving the power law index n and an intercept lnk (Fig. 1a). For Equ (6), ln$S$ forms a linear function against ln$I$. A straight line is also available with a slope still representing the power law index n, but, in this case, the intercept k' ($k' = \ln\mathrm{k} - n\ln I_0$) will be dependent on the threshold value of the stimulus and the unit used for stimulus (Fig. 1b).

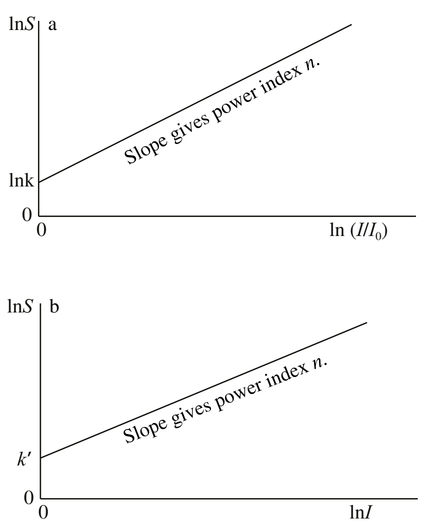

Fig. 1 A log-log plot of the modified Stevens law, where dimensionless sensory perception intensity is plotted as a functions of: (a) the relative intensity of the corresponding physical stimulus (I/I_0), and (b) the absolute intensity of the corresponding physical stimulus. The slope of the line gives the power law index, n, for both cases.

An obvious advantage of the new modified Stevens law (Equ (4)–(6)) is its dimensionless, which means that whatever dimension is used for the physical stimulus will not affect the applicability of the theory. It should also be noted that, when applying Stevens law for sensory analysis, magnitude estimation (or in log scale) would be the most appropriate approach [7,8]. However, if a linear scale is used for sensory scoring as is preferred by consumers, then the obtained sensory value can be designated as S' which is actually equivalent to ln$S$. Equ (5) may then be expressed as:

$$S' = n\ln\left(\frac{I}{I_0}\right) + \ln\mathrm{k} \quad (7)$$

where S' is the perceived intensity expressed in linear scale, or $S' = \ln S$.

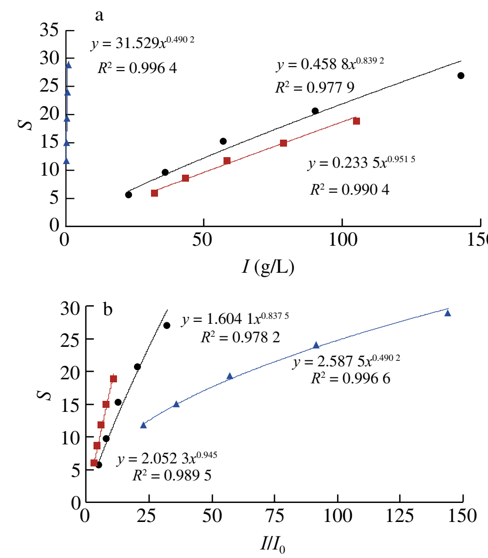

Fig. 2 Psychophysics of sweetness perception. (a) A plot of perceived sweetness intensity as a function of the concentration of sweet substances according to Stevens law. (b) A plot of the perceived sweetness intensity as a function of the ratio of the concentration of sweet substance in test sample to that of the threshold value, according to modified Stevens law. Results were presented as an average from 20 trained subjects and same power law indexes are obtained from the two cases. Open circles are for sucrose, open squares are for glucose; open triangles are for sucralose.

To confirm the applicability of the modified Stevens law, sensory analysis was organized using a magnitude estimation method [7,8]. Perceived sweetness intensity was estimated by 20 trained subjects for sucrose, glucose, and sucralose (a sweetener) solutions at a set of concentrations (g/L). Fig. 2a plots perceived sensory intensity against stimulus concentrations (g/L) based on the Stevens law, while in Fig. 2b sensory intensity is plotted against the relative intensity of the stimulus, I/I_0, the concentration ratio of the test sample to the threshold value. We can see that the perceived sweetness intensities for all three samples are in power law model in both cases. For sucralose, extremely low threshold value amplifies I/I_0 values and moves its curve from left side in Fig. 2a to far right in Fig. 2b. However, as predicted, the overall pattern remains the same for all three systems. Moreover, the power law index, n, remains the same either using the Stevens law (Equ (1)) or its modified version (Equ (4)).

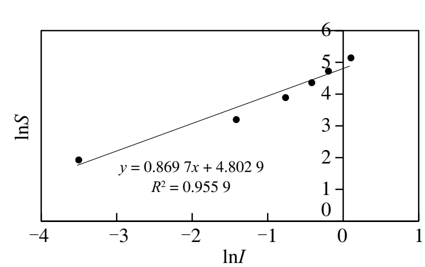

Fig. 3 A replot of the perceived saltiness intensity as a function of salt concentration (in weight percentage), according to modified Stevens law in Equ (6). Original data were obtained from Fig. 3 of the work by Suzuki et al [9].

To further confirm the feasibility of the modified Stevens law, trial analysis has also been extended to literature data. In a work by Suzuki et al. [9], psychophysics of saltiness perception was investigated for emulsion systems. Data of the saltiness intensity (shown in Fig. 3 of the paper) were selected for further analysis using modified Stevens law. The perceived saltiness intensity of salt solution is re-plotted as a logarithm function of salt concentration (in *m*/*m*, %) as shown in Fig. 3. The slope of the fitted line gives a power law index, n = 0.87, the same as the value given by the authors [9].

3. The derivation of sensory perception

Despite numerous successful cases, the application of the Stevens law appears to be much limited than it seems to be. The theory applies well to those sensory attributes that have a directly related physical stimulus. Successful cases highlighted in Table 1 are obvious examples where each perceived sensory feature has its corresponding (or at least dominating) contributing physical stimulus. However, many sensory features as a matter of fact have no direct corresponding material property but influenced by a combination of two or more physical stimuli. Therefore, these sensory terms can be called as derived sensory and such a phenomenon may be called as sensory derivation. For example, sweet-sour taste is a commonly perceived and often liked sensory feature. It is no doubt that the perceived intensity of sweet-sour taste depends on both the sweetness and the acidity of the food. Sensory combination of the two properties is much more complicated than “1 + 1” and their relationship are obviously beyond the applicability of the Stevens law. Creaminess, a well liked sensory feature originated from the presence of cream (oil/fat) in food formulations, is another good example of sensory derivation. Sufficient evidences confirm that the perceived intensity of creaminess is not in simple proportion to the quantity of cream (oil/fat) in food formulation, but is influenced drastically by other physical properties such as the viscosity and lubrication properties inside the oral cavity [10]. Color, appearance, and aroma also play a role in oil/fat perception and therefore the creaminess perception [11].

Sensory derivation also occurs commonly in the perception of food texture. For example, a group of Japanese scientist identified a total of 445 texture terms in three texture categories (mechanical, geographical, and others) in Japanese language [12]. Hanada [13] also confirmed wide diversity of texture terms and identified at least 15 basic food texture dimensions in Japanese onomatopoeic words. It is difficult to imagine each of 445 texture terms has its individually corresponding physical stimulus. Most of such texture terms are as a matter of fact sensory terms derived from different combinations of various physical stimuli.

Derivation of aroma perception may be more evident than taste and texture. Olfactory receptors are known to work based on key-and-lock mechanisms [14,15], meaning each receptor is designated to detect only for one specific molecule or a molecular group. However, consumers hardly express aroma perception in chemistry terms, but describe smells based on previous experience and its similarity to a (food) material, such as smell like an apple, a strawberry, a coffee, a cheese, and etc. Even though human beings express smell in a material-related term, there is no doubt that the perception is the result coming from the detection of tens or hundreds of aromatic molecules. This is for sure a case of derived sensory perception.

Based on above analysis, the authors believe that it is reasonable to categorize sensory attributes into two categories: primary sensory and derived sensory. Primary sensory attributes are those which have corresponding stimulus and their relationship can be properly described by the Stevens law. Derived sensory attributes are those which are related to two or more sensory stimuli working in a complicated combination. The relationship between a derived sensory feature and its corresponding stimuli is much more complicated and is beyond the applicability of the Stevens law. The lack of proper understanding of the relationship between derived sensory features and corresponding material properties is still a major barrier in applying instrumental measurements for sensory prediction, as has been highlighted recently by Peleg [16] and Nishinari et al. [17] on the cases of instrumental assessment of food texture.

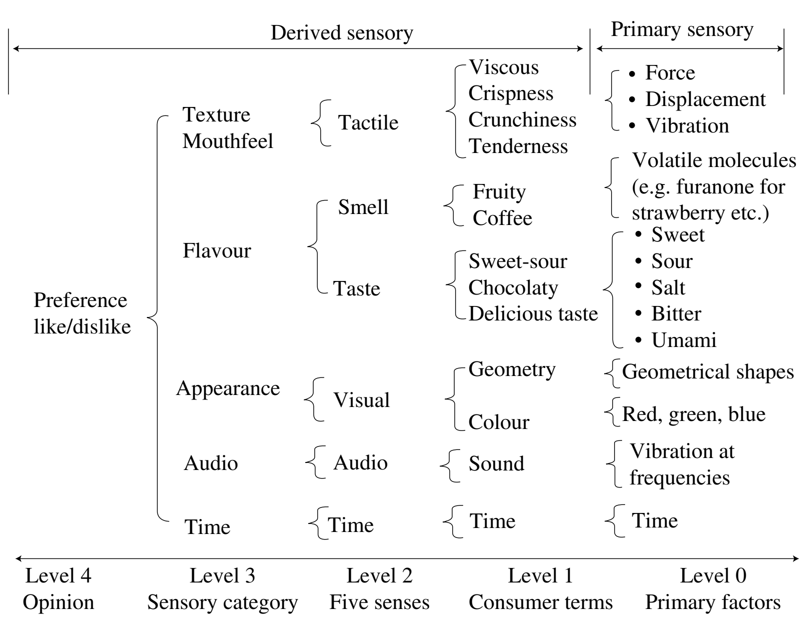

Fig. 4 The hierarchy of sensory perception, consisting of primary sensory at level 0 to derived sensory from level 1 to level 4. The primary sensory shown on the right column represents sensory features which are directly perceived from corresponding physical stimulus. Derived sensory perception are sensory features derived through a combination of different physical stimuli as well as through different levels from consumer terms at level 1 to opinion at level 4.

4. The sensory hierarchy

The derivation of sensory perception may go much further and wider. Based on the nature of the derivation and relevance, a sensory hierarchy can be constructed to give a full profile of sensory perception, from the primary sensory perception at level 0 up to opinion at level 4 (Fig. 4).

At the basic level (level 0, the right column in Fig. 4) is the primary sensation, where sensory stimuli are detected and perceived directly by human sensation cues. Such stimulation information is then picked up and analyzed by our brain for sensory interpretation. Five basic tastes are typical examples of the primary sensory perception. We tend to believe that sensations of weight and force are examples of primary sensory where the perception is made by direct tactile senses of force or pressure by the mechanoreceptors. At level 1, consumer sensory terms are produced based on the interpretation of combined primary stimuli, for example, sweet-sour for taste, viscosity for texture, coffee smell for aroma and etc. Level 2 is basically the five senses, including tactile, smell, taste, visual, and audio. Level 3 of sensory derivation corresponds to sensory categories which are so commonly acknowledged that different research communities (or sub-disciplines) are formed for each sensory category. Level 4 is the ultimate level of sensory derivation, referring to consumers' opinion about the product, like or dislike. Opinion developed at level 4, combined with the nutritional consideration and financial restriction, determines whether the consumer will buy and consume the product again in future. The sensation of time is somewhat special. It is at primary level as a standalone category. It can be an independent category but also contributes to the derivation of many other sensory attributes relating to the rate of change, such as rate of deformation, rate of flavor release and etc.

Take texture or mouthfeel perception as an example to further illustrate the hiding principles of sensory derivation. The force (stress) stimulus, the displacement sensation, and vibration sensation are probably the three core primary factors for texture sensation. The sensation of these primary cues may directly lead to the perception of some sensory features, such as weight, hardness, firmness of an object based on the force sensation; roughness sensation from displacement sensation, etc. Various combinations of these three primary factors will be able to give assessment of a number of other texture terms. For example, viscosity and thickness are two closely linked terms which are the sensory results of some primary sensory stimuli. Viscosity is a precisely defined rheological property, while thickness is a term more commonly used by consumers. For instrumental viscosity (μ) measurement, the ratio of the stress (force per unit of deformation area), σ, against the strain rate (displacement per unit of time), $\dot{\gamma}$ in Equ (8) is programmed for viscosity calculation in all modern rheometers.

$$\mu = \frac{\sigma}{\dot{\gamma}} \tag{8}$$

Human assessment of thickness is more experience-based, but internal psychophysical analysis of the perceived thickness could follow the same physical rules applied in rheometer analysis. For instance, to perceive viscosity/thickness, a fluid food sample can be placed between two fingers or between the tongue and the hard palate. The two interacting surfaces move against each other to create a controlled flow, the resistance against the deformation by the material can then be detected by mechano-receptors underneath the skin. The analysis of the perceived resistance (force) in relation to the contacting area gives stress; and the perceived displacement against the time sensation gives the rate of deformation. Combination of the two derived features will lead to the perception of thickness, just like viscosity calculation shown in Equ (8) programmed in instrumental rheometers.

5. Summary

Psychophysical process of sensory perception is an internal process and the exact of physical model of the process is still little known despite the efforts in the past. The Stevens law was probably the first such model which makes meaningful connection between the sensory perception and physical stimulus. The dimensionless Stevens law proposed in this work makes the model self-consistent and applicable in almost all scenarios, regardless the unit of the physical stimulus. Authors believe that most sensory attributes are as a matter of fact internally derived from those primarily perceived features. Therefore, a concept of sensory derivation is proposed. We believe that derivation is true for all five senses and for all four sensory categories. Despite that it is still at an early stage to develop a reliable psychophysical model for the appropriate description of derived sensory perception, important implications of sensory derivation should be recognized.

1) The Stevens law is only applicable to some limited cases where sensory perception has only one dominating corresponding material stimulus. The application becomes questionable once two or more sensory stimuli are simultaneously involved in the sensation and perception of a sensory attribute. The Stevens law is simply not designed for the analysis of derived sensory attributes.

2) A sensory attribute and its corresponding material property is conceptually different. Therefore, appropriate cautions must be taken when applying an instrument for the assessment of a sensory feature. Contributing primary sensory factors/stimuli must be properly identified before instrumental analysis is taken place. It is only when such contributing factors have been identified, appropriate methodology and models can then be established for quantitative analysis of such sensory features. For example, creaminess or fattiness perception could involve a number of physical stimuli, including at least the color, aroma, texture [11,18].

3) It is important to acknowledge that the internal mechanisms of sensory derivation are highly complicated and is still a mystery to us. Possible mathematical or psychophysical models used in our brain for sensory analysis are yet to be established before the mechanisms of derivation can be fully understood.

4) It is also very important to accept that sensory derivation could be highly individual. Different individuals may have very different internal approaches for the analysis of the perceived sensory information, caused by differences in individuals' experience, psychology, as well as physiology.

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Conflict of interest

All authors would also like to declare that results presented in this paper were obtained as a part of the employed work. No conflict of interest is involved by any author in conducting and publishing this work.

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