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A psychometric user experience model based on fuzzy measure approaches

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ABSTRACT

User experience (UX) is considered a key quality of interactive products in today's competitive mass markets and is of growing interest in both academia and industry. UX concerns the encounters a user has while interacting with products, systems, and services. It is ubiquitous, omnipresent, and dynamic in nature, referring to the non-quantifiable, subjective, affective-based, and context-dependent processes. UX is difficult for researchers to objectively and uniformly measure as it involves complex human perceptual interpretations of experiential responses with a certain degree of uncertainty, imprecision, and vagueness. Based on the user experience questionnaire (UEQ), this paper presents a psychometric UX model using fuzzy measure approaches, the purpose of which is to develop a metric for quantitative assessment of certain product UXs through a user experience index (UXI). This model enables researchers to understand users' perceptions of the interactions that constitute qualities of using a specific product. An empirical study concerning the episodic UX measures of using a set of touch mice was conducted to verify the applicability and effectiveness of the proposed UX model. The theoretical and practical implications of the UX model are also discussed.

1. Introduction

Human considerations have been systematically involved in various aspects of product or system design over the past few decades. The ways in which people interact with products or systems have also been investigated from different perspectives and various domains in a large number of studies, including human factors and ergonomics (HF&E), human-computer interaction (HCI), usability engineering (UE), user-centered design (UCD), and interaction design (IxD). Although various sophisticated user-focused theories and methodologies have been developed and employed in the literature, a gap exists between users' and designers' perspectives when taking account of user-related issues in product or system design [1,2]. To bridge this gap, an increasing interest in enhancing people's interactions with products/systems has prompted design research that focuses on the importance of a contextual survey with respect to the user's previous experience, rather than the designer's [3]. This implies that designers may leave the necessary room to spare for users and their interpretations of products/systems [4]. On the other hand, in the current knowledge-based society embedded in a high-tech global economy, industries have become aware that developing products and services is not enough, and that designing experiences is the next level of competition [5,6]. As such, product development is no longer only about implementing features and testing their usability, but about designing products that are enjoyable to use and support fundamental human needs and values [7,8]. Thus, "experience-centered" has now become a key concern of product development.

Experience is an intangible process of interaction between a person and the world that exists in the mind and is triggered by new interactions [9]. The recent shift of emphasis in the field of HCI from usability testing to experience eliciting has instigated a series of research activities in understanding and defining user experience (UX) [10–13]. UX is a multidimensional concept and various definitions have been proposed in the literature. According to ISO 9241-110:2010 [14], UX is defined as "a person's perceptions and responses that result from the use and/or anticipated use of a product, system, or service". Hassenzahl and Tractinsky [15] argued that the concept of UX attempts to go beyond the task-oriented approach of traditional HCI by bringing out aspects such as beauty, fun, pleasure, and personal growth that satisfy general human needs but have little instrumental value. UX concerns the encounters a human has while interacting with products, systems, and services [16–18]. It can be regarded holistically as a sum of the momentary constructions derived from the interaction of users with their environments. These constructions may be affected by several strands that include, but are not limited to, compositional, sensory, emotional, spatiotemporal, and interaction-based factors [19]. Various studies have been conducted with different goals, such as investigating common definitions and understanding of UX; creating appropriate concepts, frameworks and models for supporting design and development processes; and developing methods and techniques for evaluating

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UX [20–22]. However, discussions on the theoretical roots and foundations for UX research seem to lag behind [23,24].

UX is a term used to describe a user's perceptions and responses that result from the use of a product, system, or service in a particular usage context. The perceptions and responses can be physical, psychological, or both, while the context can be a momentary (a specific change of feeling during interaction), episodic (appraisal of a specific usage episode), or cumulative period of experience (views on a system as a whole, after having used it for a while). It is often challenging to measure UX as it is ubiquitous, omnipresent, and dynamic in nature. Although a diversity of UX models have been developed during the past decade [25–32], systematic research on how to measure UX is still lacking [21,33–35]. Most existing guidelines on UX measures are based on traditional usability metrics [36]. However, usability tests tend to focus on objective task performance whereas UX focuses on subjectively interpreted experiences [37]. Consequently, it is difficult to objectively and uniformly measure UX by a conventional research approach as such experiences involve non-quantifiable, subjective, and affective-based processes and entail the human perceptual interpretation of experiential responses, which inevitably involves some uncertainty, imprecision, and vagueness.

A psychometric model employs refined theories and techniques for a specific psychological measurement task, which usually involves the construction and validation of assessment instruments such as questionnaires, tests, and evaluators' judgments. Fuzzy measures are typically monotonic set functions used to model either uncertainty or the strength of coalition of criteria in multi-criteria decision-making [38–40]. The use of fuzzy measure approaches provides opportunities to quantify psychometric items and user perceptions under uncertainty induced by vagueness and imprecision in item features and user responses. Specificity measures of fuzzy sets offer a degree of the utility of information contained in a fuzzy set, while the entropy measures provide a degree of fuzziness for the fuzzy set, which can be computed by the premises/outputs of an inference to determine an amount of uncertainty crispness in the process [41]. UX can be classified into two types of models, namely qualitative and quantitative. The qualitative UX models usually identify measurements and structures of UX, while the quantitative ones are employed to develop UX measure approaches for a particular domain. A well-tested model enables UX measures to be meaningful and validated, allowing the nature of UX constructs to inform how UX is operationalized and measured [27]. Most researchers have recognized the necessity of quantifying UX [29,32,34,42,43]. However, in the literature, only a few quantitative models have thus far been proposed [44,45]. Within this context, this paper presents a psychometric UX model based on fuzzy measure approaches, the purpose of which is to develop a metric for measuring the UX quality of interactive products through a user experience index (UXI). This model empowers researchers to understand how users perceive and value products; thus ensuring positive UX, guiding meaningful product design, and leading to more desirable products for users.

The remainder of this paper is organized as follows. Section 2 introduces the theoretical fundamentals of user experience constructs, fuzzy sets and fuzzy measures, and measures of fuzziness. Section 3 describes the proposed UX model, while Section 4 presents an empirical study to demonstrate the implementation process and applicability of the proposed model. A discussion is given in Section 5 and conclusions and recommendations for further research are offered in Section 6.

2. Theoretical fundamentals

Psychometric UX modeling involves two major tasks, namely: (1) the construction of UX instruments and procedures for measurement; and, (2) the development and refinement of theoretical approaches to measurement. In this section, some important fundamentals used in the proposed model are addressed. These fundamentals include the constructs of UX, fuzzy sets and fuzzy measures, and measures of fuzziness.

2.1. Constructs of user experience

UX can be regarded as a cognitive process that can be modelled and measured [46]. Common subjective UX measure methods include interviews, questionnaires, surveys, and often, a combination of these. In order to make UX measurable and quantifiable, the constructs and dimensions of UX must be identified. Many studies have investigated the structure of dimensions among a latent construct and its items [42,47–49]; however, there is no agreement in the literature on the exact measures for assessing the overall UX of a product since different products aim at different kinds of experiences. Generally speaking, UX constructs involve the general impression toward a product and extend the usability approach to cover issues beyond pragmatic quality for fulfilling "do-goals" with hedonic quality for satisfying "be-goals" [50,51].

UX involves experiential, affective, meaningful, and valuable aspects of product use. Law and van Schaik [27] described how UX needs to be self-reported, since it is a personal and experiential quality, in contrast to the goal and task orientation of more established usability measures. However, Bargas-Avila and Hornbæk [52] found in an inventory of UX research that half of the publications that used self-report questionnaires employed self-developed instruments without providing readers with information about which items were used or on what basis these items were formulated. Tonetto and Desmet [42] further demonstrated that researchers are more likely to end up with consistent research instruments when using a natural and domain-specific approach to develop user experience surveys. In this study, the User Experience Questionnaire (UEQ) is employed as the UX instrument for the psychometric UX modeling. The UEQ was developed by Laugwitz et al. [53] through a data analytical approach, and is a validated tool widely used for measuring the UX of interactive products [54–57]. The UEQ is based on a hierarchical structure of UX constructs, and consists of 6 dimensions, each of which comprises 4 or 6 sets of bipolar items, as shown in Table 1.

The UEQ is currently available in 20 languages (German, English, French, Italian, Russian, Spanish, Portuguese, Dutch, Turkish, Chinese, Japanese, Indonesian, etc.), and contains a data analysis tool and a benchmark data set for UX practitioners to interpret the test results (please refer to www.ueq-online.org). It is based on the semantic differential (SD) format designed to cover a comprehensive impression of user experience, measuring both classical usability aspects (efficiency, perspicuity, and dependability) as well as UX aspects (novelty and stimulation). As shown in Appendix A, the UEQ consists of 26 items and the order of positive and negative worded terms for each given item was randomized in the questionnaire. It employs a 7-point scale to gather respondents' ratings for each perceptual item and supports immediate responses for respondents to express feelings, impressions and attitudes toward the use of an interactive product.

2.2. Fuzzy sets and fuzzy measures

Fuzzy sets were introduced by Zadeh [58] as a generalization of crisp sets for representing imprecision or vagueness in everyday life. A fuzzy set is defined by its membership function. Let X denote a universal set. A fuzzy set A in X is characterized by its membership function

$$\mu_A: X \to [0, 1] \tag{1}$$

where [0,1] denotes the real number interval from 0 to 1, inclusive.

The value of membership grade indicates the degree of element u belonging to fuzzy set A for each $u \in X$, and A is defined as a collection of ordered pairs that can be expressed by the following notations [59]:

$$A = \frac{\mu_1}{u_1} + \frac{\mu_2}{u_2} + \cdots + \frac{\mu_n}{u_n} = \sum_{i=1}^{n} \frac{\mu_i}{u_i}$$

Table 1
List of UX constructs for the psychometric UX modeling.

Construct	Dimension	Description of question	Bipolar item
General impression toward the product	Attractiveness (u_1)	Do users like or dislike the product?	enjoyable-annoying (u_{11})
			good-bad (u_{12})
			pleasing-unlikable (u_{13})
			pleasant-unpleasant (u_{14})
			attractive-unattractive (u_{15})
			friendly-unfriendly (u_{16})
Pragmatic quality	Perspicuity (u_2)	Is it easy to understand how to use the product?	understa-incomprehensible (u_{21})
		Is it easy to get familiar with the product?	easy to learn-difficult to learn (u_{22})
			simple-complicated (u_{23})
			clear-confusing (u_{24})
	Efficiency (u_3)	Is it possible to use the product quickly and efficiently?	fast-slow (u_{31})
			efficient-inefficient (u_{32})
			practical-impractical (u_{33})
		Does the user interface look organized?	organized-cluttered (u_{34})
	Dependability (u_4)	Does the user feel in control of the interaction?	predictable-unpredictable (u_{41})
			supportive-obstructive (u_{42})
			secure-insecure (u_{43})
		Is the interaction with the product secure and predicable?	meets expectations-does not Meet expectations (u_{44})
Hedonic quality	Stimulation (u_5)	Is it interesting and exciting to use the product?	valuable-inferior (u_{51})
			exciting-boring (u_{52})
			interesting-not interesting (u_{53})
		Does the user feel motivated to use the product again?	motivating-demotivating (u_{54})
	Novelty (u_6)	Is the design of the product innovative and creative?	creative-dull (u_{61})
			inventive-conventional (u_{62})
			leading edge-usual (u_{63})
		Does the product grab the user's attention?	innovative-conservative (u_{64})

$$= \int_X \frac{\mu_A(u)}{u} \tag{2}$$

where the term $\frac{\mu_i}{u_i}$, $i = 1, 2, \cdots, n$ signifies that μ_i is the membership grade of u_i in A; the plus sign represents the union; and the integral sign represents the fuzzy set A when X is not finite (an interval of real numbers).

The definition of normalization and convexity plays an important role in fuzzy set theory. A fuzzy set A is said to be normalized when at least one of its elements attains the maximum possible membership grade (i.e., $max_{u \in X} \mu_i = 1$); and if the membership function $\mu_A(x)$ is a monotone increasing function for $x < c$ and a monotone decreasing function for $x > c$, where $\mu_A(c) = 1$, it can be considered a convex fuzzy set. If a convex and normalized fuzzy set, whose membership function is piecewise continuous, is defined on $\boldsymbol{R}$, it can be classified as a fuzzy number.

The concept of α-cut is a means to convert a fuzzy set into a universal set, which is very significant in the relationship between fuzzy sets and crisp sets, and is also useful for defining the arithmetic operations on fuzzy numbers. As shown in Fig. 1, the α-cut of fuzzy set A represented by the Gaussian membership function (GMF) ($\mu_A(x) = e^{-\frac{1}{2}(x - c/\sigma)^2}$, where c is the center (i.e., mean) and σ is the width (i.e., standard deviation) of the fuzzy set) is the interval of real numbers $[p,q]$, and all the numbers in this interval have a degree of membership greater than or equal to the specified value of α ($0 < \alpha \leq 1$). The α-cut of fuzzy set A can be expressed as below [59,60]:

$$A_\alpha = \{x \in X \,|\mu_A(x) \geq \alpha\} \tag{3}$$

A measure on a fuzzy set is a systematic way to assign a value to each subset of the fuzzy set, which can be thought of as making a precise notion of "size" or "volume" for the fuzzy set. Let A be a discrete fuzzy set and u_i be the subset of A that contains a finite number of elements u_{ij}. The aggregation, defined as the integration of a function (the data of elements to be aggregated) with respect to a fuzzy measure, can be formularized as

$$\mu_A(u_i) = \frac{\sum_{j=1}^{m} r_{ij} \cdot w_{ij}}{\sum_{j=1}^{m} w_{ij}} = \frac{\int_{\propto=0.063}^{1} (r_{i1} \times w_{i1})_\propto + (r_{i2} \times w_{i2})_\propto + \cdots + (r_{im} \times w_{im})_\propto}{\int_{\propto=0.063}^{1} (w_{i1})_\propto + (w_{i2})_\propto + \cdots + (w_{im})_\propto} \tag{4}$$

where

$\mu_A(u_i)$ represents the resultant membership function of the i^{th} subset; r_{ij} denotes the rating variable of the j^{th} element of the i^{th} subset; and, w_{ij} is the weight variable of the j^{th} element of the i^{th} subset.

Fuzzy variables r_{ij} and w_{ij} are fuzzy numbers. In this study, assessment was based on 7-point rating scales described by the continuous GMFs (where $2\sigma^2 = 0.01$) shown in Fig. 2. GMFs can be regarded as a normally-distributed ordered set of rating scales and are suitable for problems requiring continuously differentiable curves to capture the vagueness of rating responses. As the GMF is symmetric around its center value c_i (where $c_i = 0, 0.167, 0.333, 0.5, 0.667, 0.833$, or 1), the fuzzy numbers are represented with interval notations as $F = [f_L, f_R]$. The aggregation with continuous α-cuts ($0.063 \leq \alpha \leq 1$) is a combination of extended algebraic operations (addition, subtraction, multiplication, and division) based on interval arithmetic operations and requires that every fuzzy number is represented by a continuous membership function and can be completely defined by its family of α-cuts [60–62]. For $r_\propto = [a, b]$ and $w_\propto = [c, d]$, the arithmetic operations for Eq. (4) can be expressed as [63]

- $(r \times w)_\propto = r_\propto \cdot w_\propto = [a, b] \cdot [c, d] = [\wedge(ac, ad, bc, bd), \vee(ac, ad, bc, bd)] = [e, f] = z_\propto$;
- $(z_1)_\propto + (z_2)_\propto + \cdots + (z_m)_\propto = [e_1, f_1] + [e_2, f_2] + \cdots + [e_m, f_m] = [(e_1 + e_2 + \cdots + e_m), (f_1 + f_2 + \cdots + f_m)] = [\varepsilon, \eta]$;
- $(w_1)_\propto + (w_2)_\propto + \cdots + (w_m)_\propto = [c_1, d_1] + [c_2, d_2] + \cdots + [c_m, d_m] = [(c_1 + c_2 + \cdots + c_m), (d_1 + d_2 + \cdots + d_m)] = [\rho, \sigma]$;

 and provided that $0 \notin [\rho, \sigma]$
- $\frac{[\varepsilon, \eta]}{[\rho, \sigma]} = [\varepsilon, \eta] \cdot \left[\frac{1}{\sigma}, \frac{1}{\rho}\right] = \left[\wedge\left(\frac{\varepsilon}{\rho}, \frac{\varepsilon}{\sigma}, \frac{\eta}{\rho}, \frac{\eta}{\sigma}\right), \vee\left(\frac{\varepsilon}{\rho}, \frac{\varepsilon}{\sigma}, \frac{\eta}{\rho}, \frac{\eta}{\sigma}\right)\right]$

The result of the arithmetic operations is a crisp set (interval) that represents the α-cut of the fuzzy set obtained by operating on fuzzy numbers r_{ij} and w_{ij}. Through the aggregation operations, the family of α-cuts defined as the resultant membership function of the measured subset can be presented as a convex and normalized fuzzy set, $s_i(x)$, which is also classified as a fuzzy number. Taking advantage of the

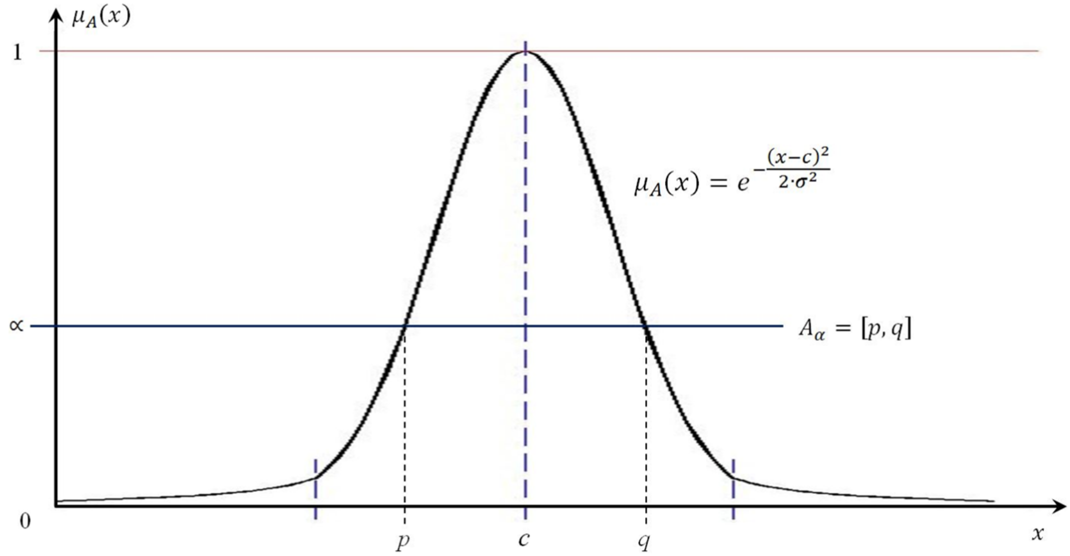

Fig. 1. Example of a membership function of fuzzy set A and its α-cut.

center-of-gravity (COG) defuzzification method shown in Eq. (5), the quantitative value of the measured subset, $\bar{\mu}_A(s_i)$, can be derived. These defuzzified fuzzy numbers must be mapped into (0,1) intervals (i.e., $\hat{\mu}_A: X \to (0, 1)$) in order to obtain a set of quantitative values representing the derived membership grades, $\hat{\mu}_A(s_i)$, for the fuzzy measure and fuzzy entropy operations. An example of the aggregation and defuzzification result is also shown in Fig. 2.

$$\bar{\mu}_A(s_i) = \frac{\int_g^h s_i(x)\cdot x dx}{\int_g^h s_i(x) dx} \tag{5}$$

where

$s_i(x)$ represents the resultant fuzzy number of the measured subset i; and,
g and h are the respective lower and upper limits of the support of the fuzzy number.

An σ-algebra over a set A is an algebra closed under countable unions. Let A be a non-empty set and u_i a σ-algebra defined on A. A fuzzy measure m defined on the measurable space (A, u_i) is a set function $m: u_i \to [0, \infty)$ which verifies the following axioms: (1) $m(\varnothing) = 0$; and (2) $u_1, u_2 \in u_i,\ u_1 \subseteq u_2 \Rightarrow m(u_1) \leqslant m(u_2)$ [64,65]. Based on the σ-additive set function, the fuzzy measure of A can be expressed as

$$m(A) = \bigcup_{i=1}^{n} u_i = \sum_{i=1}^{n} \hat{\mu}_A(u_i) \tag{6}$$

where

$\hat{\mu}_A(u_i)$ is the assigned quantitative value, indicating the degree of evidence or belief that subset u_i belongs to A in X.

2.3. Measures of fuzziness

In general performance, the membership function of a fuzzy set is determined by researchers subjectively, and the shape of a membership function always represents the knowledge grade of the elements in the fuzzy set. For researchers, every membership function presents the fuzziness of the corresponding fuzzy set, which means that characterization and quantification of fuzziness in fuzzy arithmetic are important issues [66]. Measures of fuzziness have been one of the significant subjects associated with the development of fuzzy set theory. Shannon [67] introduced the concept of information entropy by associating uncertainty with every probability distribution $P = (p_1, p_2, \cdots, p_n)$ and proposed a unique function $S(P) = -\sum_{i=1}^{n} p_i log_b p_i$ used as a measure of uncertainty and information. Inspired by the Shannon entropy of

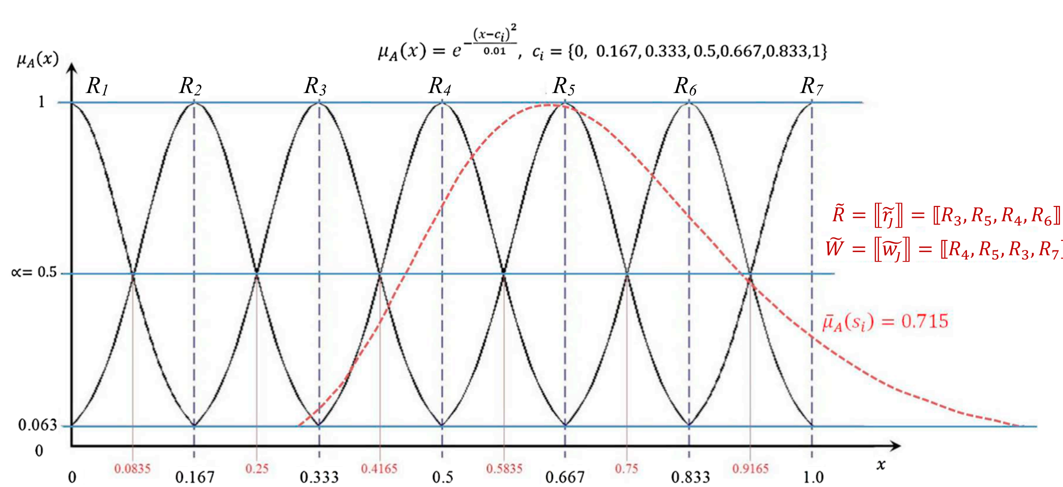

Fig. 2. Seven-point rating scales characterized by continuous Gaussian membership functions.

random variables, fuzzy entropy was first initialized by Zadeh [68] to quantify fuzziness by defining the entropy of a fuzzy event as a weighted Shannon entropy value. Over the past few decades, fuzzy entropy has been studied by many researchers from different aspects of theory and application [69–71]. De Luca and Termini [72] first axiomatized nonprobabilistic entropy and proposed the parametrized entropy measure as $E_k(A) = D_k(A) + D_k(A^c)$, where $k > 0$ and $D_k(A) = -k\sum_i \mu_A(u_i) log\mu_A(u_i)$. The De Luca-Termini axioms were formulated to describe the fuzziness degree of a fuzzy set and have been adapted to other types of fuzzy sets, such as intuitionistic [73], interval-valued [74], interval-valued intuitionistic [75], or interval-valued hesitant fuzzy sets [76]. Kaufmann [77] suggested that the entropy of a fuzzy set can be measured through the metric distance between its membership function and that of its nearest crisp set (i.e., $K_p(A) = (2/n^{1/p}) l^p(A, \bar{A})$ for $p \geq 1$, where the normalizing constant stems from the metrical fact that $0 \leq l^p(A, B) \leq n^{1/p}$, and $l^p(A, B)$ represents the distance between fuzzy sets A and B). Yager [78] defined the concept of a fuzziness measure as the degree of distinction between the fuzzy set and its complement (i.e., $Y_p(A) = 1 - l^p(A, A^c)/[l^p(A, \emptyset)]^p$ for $p \geq 1$). Kosko [79] argued that a well-defined fuzzy entropy measure must satisfy the four De Luca-Termini axioms. He proposed the fuzzy entropy as the ratio of the distance between a fuzzy set and its nearest and furthest crisp sets (i.e., $R_p(A) = l^p(A, \bar{A}) \big/ l^p(A, \underline{A})$ for $p \geq 1$, where $\bar{A}$ is the nearest crisp set and $\underline{A}$ is the furthest crisp set).

Measures of fuzziness, in contrast to fuzzy measures, indicate the degree of fuzziness of a fuzzy set. The entropy of a fuzzy set is a measure of the fuzziness of a fuzzy set. Let $\mu_A(x)$ be the membership function of fuzzy set A for $x \in X$, where X is finite; the measure of fuzziness $d(A)$ satisfies the following four De Luca-Termini axioms:

(1) $d(A) = 0$ if and only if A is a crisp set in X.
(2) $d(A)$ assumes a unique maximum if $\mu_A(x) = 0.5$, $\forall\, x \in X$.
(3) $d(A) \geq d(A')$ if A' is "crisper" than A, i.e., if $\mu_{A'}(x) \leq \mu_A(x)$ for $\mu_A(x) \leq 0.5$, and $\mu_{A'}(x) \geq \mu_A(x)$ for $\mu_A(x) \geq 0.5$.
(4) $d(A^c) = d(A)$, where A^c is the complement of A, i.e., $A^c(x) = 1 - A(x)$.

The entropy as a measure of a fuzzy set $A = \{u, \mu_A(u)\}$ is defined as follows [72]:

$$d(A) = H(A) + H(A^c),\ u \in X \tag{7}$$

$$H(A) = -K\sum_{i=1}^{n} \mu_A(u_i) log_b(\mu_A(u_i)) \tag{8}$$

where n is the number of elements in support of A; b is the base of the logarithm used; and K is a positive constant.

Using Shannon's function $S(x) = -xlog_b x - (1-x)log_b(1-x)$ measured in nats (i.e., $b = e$, the base of the natural logarithm), the entropy d as a measure of the fuzziness of fuzzy set $A = \{u, \mu_A(u)\}$, $u \in X$ can be expressed as below:

$$d(A) = K\sum_{i=1}^{n} S(\hat{\mu}_A(u_i)) = K\sum_{i=1}^{n} -\hat{\mu}_A(u_i)\ln\hat{\mu}_A(u_i) - (1-\hat{\mu}_A(u_i))\ln(1-\hat{\mu}_A(u_i)) \tag{9}$$

where $\hat{\mu}_A(u_i)$ is the derived membership grade of fuzzy set A, indicating the degree of evidence or belief that subset u_i belongs to A in X.

Eq. (9) is called the entropy of fuzzy set A, or the fuzzy entropy of A, whose meaning is quite different from that of classical entropy since no probabilistic concept is needed to define it. For $K = 1/n$, $d(A)$ is called the normalized entropy of fuzzy set A, indicating an average measure of fuzziness. Yager [78,80] suggested that a fuzziness measure essentially attempts to evaluate the lack of distinction between a set and its negation. For a single element (i.e., $i = 1$), the diagram of function $d(A)$ is convex and symmetrical, and the maximum of $d(A)$ appears at $\hat{\mu}_A(u_i) = 0.5$ (i.e., monotonically increasing in $\hat{\mu}_A(u_i) = (0, 0.5]$ and monotonically decreasing in $\hat{\mu}_A(u_i) = [0.5, 1)$). Consequently, fuzzy entropy can be used as a measure of the fuzziness degree with the derived membership grades of a fuzzy set. In other words, the larger the entropy value, the more fuzzy the characterization and quantification of the fuzzy set is.

3. Proposed model

Based on the theoretical fundamentals given in Section 2, the implementation steps of the psychometric UX model are elaborated as follows:

Step 1: Select a set of products as samples for UX measures.

$$\mathrm{P} = \{P_k\ |k = 1, 2, 3, \cdots\} \tag{10}$$

Step 2: Construct a fuzzy set of the UX measure.

Based on the hierarchical UX constructs given in Table 1, a fuzzy set of the UX measure can be constructed as

$$U_k = \sum_{i=1}^{6} \frac{\mu_i}{u_i} = \frac{\mu_1}{\text{Attractiveness}} + \frac{\mu_2}{\text{Perspicuity}} + \frac{\mu_3}{\text{Efficiency}} + \frac{\mu_4}{\text{Dependability}} + \frac{\mu_5}{\text{Stimulation}} + \frac{\mu_6}{\text{Novelty}} \tag{11}$$

where

μ_i is the membership grade of fuzzy set U_k, representing the degree of dimension u_i (u_i comprising a finite number of items u_{ij}) belonging to the UX set of the k^{th} product sample.

Step 3: Determine fuzzy variables of ratings and weights.

Determining the relative importance of attributes (weights of criteria) is a crucial task for a hierarchical evaluation. To establish priorities of user preference relations, respondents are divided into expert and user groups. The expert group is tasked with determining the weight variables for the UX items, while the user group derives the rating variables for the product samples. According to the UEQ format, the evaluation grades are 7-point rating scales characterized by the continuous GMFs shown in Fig. 2. These scales are quantified with three types of number using different α-cut levels with their associated membership functions. To establish priorities of preference relations, cardinal numbers (at $\propto = 1$) confer a numerical value to the corresponding 7-point rating scales for statistical analysis such as means, standard deviations, and reliability and validity of the questionnaire responses. Interval numbers (at $\propto = 0.5$) are used to convert the means of the respondents' assessments into fuzzy variables (Gaussian fuzzy numbers), taking into account the fact that all respondents' assessments have some degree of inherent uncertainty. Fuzzy numbers ($\propto \in [0.063, 1]$) are used as fuzzy variables for the aggregation operations that allow the incorporation of uncertainty, imprecision, and subjective vagueness into the perceptual interpretations of the UX measure. The numerical definitions of the 7-point rating scales are given in Table 2.

According to the UEQ shown in Appendix A, respondents evaluate the selected product samples and indicate their choices from a set of semantic differential items after completing a UX trial. The evaluation results are classified into numerical rating variables, where the scale order of positively and negatively worded terms is transformed into a consistent 7-point rating scale using the corresponding cardinal number such that a higher rating value indicates a more positive user experience. By using the weighting method proposed by Chou [81,82], the numerical weight variables can be derived through eigenvalue algorithms. Further fuzzifying the derived numerical variables according to their corresponding interval numbers, the fuzzy rating variables $\widetilde{R}_k$ ($\widetilde{R}_k = [\![\widetilde{r}_{ij}]\!]$) and fuzzy weight variables $\widetilde{W}$ ($\widetilde{W} = [\![\widetilde{w}_{ij}]\!]$) are determined, where $\widetilde{R}_k$ represents the rating variables of the k^{th} product sample, while $\widetilde{r}_{ij}$ and $\widetilde{w}_{ij}$ are Gaussian fuzzy numbers, as given in Table 2.

Table 2
Numerical definitions of the 7-point rating scales.

Rating scale R.S.	Fuzzy number $\propto \in [0.063, 1]$	Interval number at $\propto = 0.5$	Cardinal number at $\propto = 1$
R_1	[0, 0.167]	[0, 0.0835)	0
R_2	[0, 0.333]	[0.0835, 0.25)	0.167
R_3	[0.167, 0.5]	[0.25, 0.4165)	0.333
R_4	[0.333, 0.667]	[0.4165, 0.5835]	0.5
R_5	[0.5, 0.833]	(0.5835, 0.75]	0.667
R_6	[0.667, 1]	(0.75, 0.9165]	0.833
R_7	[0.833, 1]	(0.9165, 1]	1

Step 4: Measure the UX set of the product sample.

By substituting the corresponding two sets of fuzzy variables into Eq. (4) to perform the aggregation operations, the resultant membership functions of the corresponding evaluated dimensions can be obtained. Eq. (5) is then used to defuzzify these fuzzy numbers for each dimension. These defuzzified fuzzy numbers are further mapped into (0,1) intervals to obtain a set of derived membership grades, $\hat{\mu}_U(u_i)$, for the following fuzzy measure and fuzzy entropy operations (which involve the natural logarithm function).

Step 5: Derive the user experience indexes (UXIs) for the selected samples.

In order to measure the desirable degree of a product's UX, a user experience index (UXI) is defined as the ratio of the normalized fuzzy measure of the UX set to its normalized fuzzy entropy. Based on the aggregation results, the fuzzy measure is used to derive the degree of the utility of information contained in the UX set while the fuzzy entropy is to mediate the effect of fuzziness resulting from the lack of crisp distinction between the UX dimensions belonging and not belonging to the UX set. Moreover, it is used as a metric for measuring the desirable degree of a product's UX quantitatively, and is formulized as

$$\mathrm{UXI} = \frac{m(U_k)}{d(U_k)} = \sum_{i=1}^{6} \frac{\hat{\mu}_U(u_i)}{-\hat{\mu}_U(u_i)\ln\hat{\mu}_U(u_i) - (1-\hat{\mu}_U(u_i))\ln(1-\hat{\mu}_U(u_i))} \tag{12}$$

where the membership grade, $\hat{\mu}_U(u_i)$, of fuzzy set U_k is a crisp number in (0,1), indicating the degree of evidence or belief that UX dimension u_i belongs to the UX set of the k^{th} product sample.

People may naturally tend to provide similar, "middle-of-the-road" responses or ratings for multiple items when they are unable to hold very certain opinions toward the question options. This kind of fuzziness can be regarded as a central tendency bias which occurs when respondents avoid using extreme ends of the rating scale and instead give an answer that is closer to the center of the options. As shown in Fig. 3, for a single dimension (i.e., $i = 1$), the UXI curve is monotonically increasing and has a steeper slope in both sides of the curve (i.e., the amount of change in $f(x)$ is much more than that of change in x), particularly when x approaching to 1 ($0 < x < 1$). This is mainly due to the utilization of fuzzy entropy which can mitigate the impact of central tendency bias as well as gives reliable results for the UX measure. By substituting the corresponding membership grade values into Eq. (12), the UXIs of the measured product samples can be derived; the higher the UXI value, the more desirable the evaluated product is.

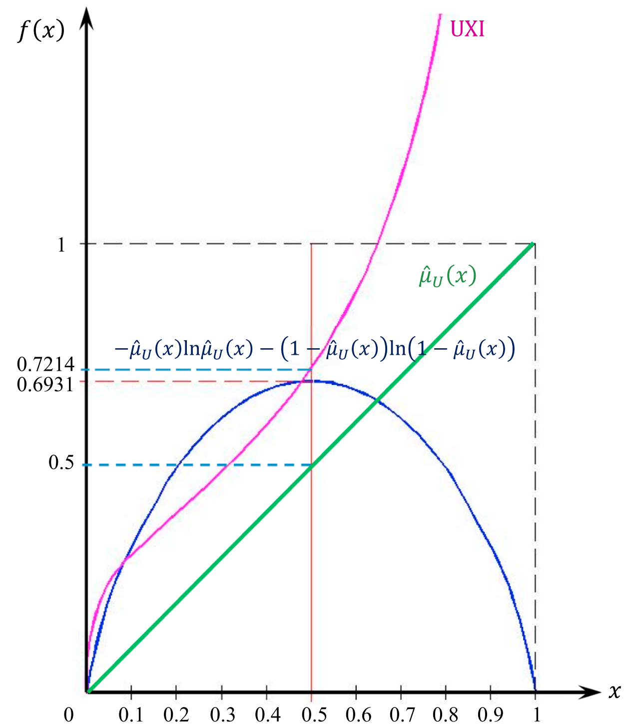

Fig. 3. Functional diagrams of fuzzy measure, fuzzy entropy, and UXI, respectively.

4. Empirical study

A computer mouse is a peripheral device used to control a cursor in two dimensions in a graphical user interface (GUI). It typically features two buttons and a scroll wheel, which can also act as a third button. With the popularity of smartphones, tablets, and many types of information appliances, touchscreens have become increasingly common for users to interact with GUIs directly on the screen. Microsoft has also provided a new GUI that supports both desktop and touch devices since Windows 8. In keeping with the touchscreen trend, the touch mouse, a new type of computer mouse, offers a blending for input and manipulation that is halfway between a traditional mouse and touchscreen. In this section, an empirical study concerning the episodic UX measures of a set of touch mice is presented to demonstrate the implementation process and applicability of the proposed UX model. The experiment consisted of two parts: (1) a pilot test for determining the item weights; and, (2) the UX measure for the selected product samples.

4.1. Participants

The empirical study involved 5 (right handed) experts and 20 (right handed) users in the UX measure task. All participants were required to have familiarity with the Windows 8 operating system. Each expert had at least 5 years of work experience in product design. A total of 20 university students were recruited to evaluate the product samples. These subjects consisted of 10 females and 10 males, ranging in age from 20 to 24 years (Mean = 20.85, S.D. = 0.988). Each participant received remuneration (NT$ 300 per student and NT$ 1000 per expert) as compensation for the time and effort he/she spent participating in the experimental study.

4.2. Product samples

Six touch mice were selected as product samples to test the proposed model for measuring the UX of these alternative products. Product features of the selected touch mice are listed in Table 3.

4.3. Experimental design and procedures

The UX experiment conducted in a laboratory at I-Shou University aimed at uncovering how target users perceive the selected touch mice after interacting with them. A SONY VAIO laptop (SVS15126PW/B, i7-3632) with a 15.5″ LED backlit Full HD display and the Windows 8.1 operating system (64-bit, Traditional Chinese version) was used as the test platform for the UX experiment (see Fig. 4). The UX test required participants (both the experts and the users) to perform defined tasks

Table 3
List of the 6 selected product samples for the UX measure.

Sample 1		Sample 2	
 Logitech Zone Touch MouseT400	Product Features: ● Connectivity: 2.4 GHz wireless (USB Connector) ● Power: 2 AA batteries ● 105(L)x61(W)x31(H)mm, 137 g ● Hybrid traditional-and-touch mouse for Windows 8: Dedicated touch zone strip plus familiar mouse buttons and precision for simple, easy navigation.	 Microsoft Sculpt Touch Mouse	Product Features: ● Connectivity: Bluetooth wireless ● Power: 2 AA batteries ● 99(L)x64(W)x33(H)mm, 140 g ● Four-way touch scrolling: Scroll vertically and horizontally using the sleek touch strip. Flick up, down, and side to side to navigate spreadsheets, long documents, web pages and the new features of Windows 8.
Sample 3		**Sample 4**	
 Rapoo T6 Touch Mouse	Product Features: ● Connectivity: 2.4 GHz wireless (USB Connector) ● Power: 1AA battery ● 114(L) × 57(W) × 24(H)mm, 108 g ● Intelligent Multi-Touch technology brings a driving gesture for mouse. Multi-Touch functions: left click, right click, vertical scroll, horizontal scroll.	 ATake Touch Mouse	Product Features: ● Connectivity: 2.4 GHz wireless (USB Connector) ● Power: 2 AAA batteries ● 105(L) × 55(W) × 22(H)mm, 84 g ● ATake buttonless touch scrolling mouse adapts the unique "touch to scroll" design idea which allows users to lightly tip the casing for executing the commands.
Sample 5		**Sample 6**	
 Microsoft Arc Touch Mouse	Product Features: ● Connectivity: 2.4 GHz wireless (USB Connector) ● Power: 2 AAA batteries ● 111(L) × 58(W) × 32(H)mm, 108 g ● Touch to scroll, click, tap, flick, and control. Quickly brush up or down with finger(s) to flick into hyper fast vertical scrolling for smooth, intuitive navigation.	 Logitech Ultrathin Touch Mouse T630	Product Features: ● Connectivity: Bluetooth wireless ● Power: Rechargeable ● 85(L) × 59(W) × 18(H)mm, 90 g ● Experience new Windows 8 navigation: effortlessly and confidently. Simplify the touch navigation experience with natural, intuitive gestures.

with each of the 6 selected samples. The drivers and gesture software for each tested mouse were pre-loaded into the system, and each product was tested for about 20 min (including 5 min for the questionnaire responses) for a total testing time of approximately 2 h per subject.

The Windows 8 touch language includes: press and hold to learn, tap for primary action, slide to pan, swipe to select, pinch and stretch to zoom, turn to rotate, swipe from edge for app commands, and swipe from edge for system commands. Moreover, touch mice enhance user interaction with the computer via the aforementioned gestures. Referring to the Windows 8 user experience guidelines created by Microsoft, the UX test comprises the following 8 tasks:

Task 1-Scrutinizing the mouse (about 2 min):

Read the experimental procedure outline and the evaluated mouse's touch gesture reference guide and then scrutinize the mouse before use, including its appearance, size, weight, materials, etc.

Task 2-Installing the mouse (about 1 min):

Install the mouse and connect it to the laptop through the USB receiver or wireless Bluetooth.

Task 3-Browsing maps (about 4 min):

Open the built-in Maps App from the Start screen and search for the location of the 8 designated cities (Kaohsiung/I-Shou University, Bangkok, Paris, London, New York, Tokyo, Beijing, and Taipei/Taipei 101 (Taipei World Financial Center) in order) by using the mouse (employing the zooming and panning functions).

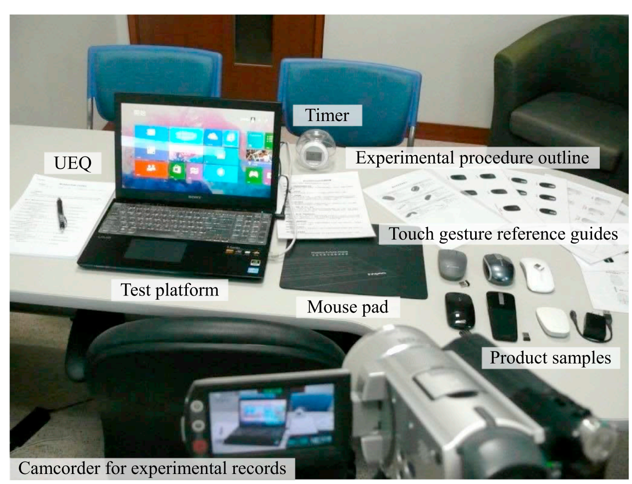

Fig. 4. Experimental environment for the UX test.

Task 4-Creating a folder (about 1 min):

Create a new folder on the Windows desktop and move it to the upper-right corner of the screen (employing the right-click and dragand-drop functions).

Task 5-Copy and paste operations (about 2 min):

Copy a paragraph of text from the designated Adobe PDF file and paste it into a Word document (employing the left/right button clicking, holding, and dragging functions).

Task 6-Image inserting and file saving operations (about 2 min):

Insert a designated image (the evaluated product sample) into the Word document and save the document (using the serial number of the tester plus the sample number as the file name) to the created folder (employing the left/right button clicking and touch gesture scrolling functions).

Task 7-Sending emails (about 2 min):

Send the document file (using the tester's own webmail account) to the assigned email address.

Task 8-Finishing the tasks (about 1 min):

Delete the folder and then disconnect the wireless mouse from the laptop.

Questionnaire response (about 5 min):

Respond to the questionnaire.

Before the UX test began, the experimenter provided a summary of the procedure. Each participant was asked to perform the 8 designated tasks with each of the selected touch mice. After finishing the testing tasks, the UEQ was immediately given to the participants (see Appendix A). The participants were instructed to respond to the questions according to their actual experience and perception of using the product samples. In addition to the UX testing, the experimenter interviewed the experts and asked for their opinions about the priorities of the 26 items corresponding to the 6 UX dimensions. The purpose of the expert interview was to verify the weight variables elicited from the proximity matrix of the experts' preference relations using the eigenvalue algorithms.

4.4. Pilot test

The purpose of the pilot test was to determine the item weights through expert assessments. The five experts directly evaluated the product samples according to the UX testing results. The means of the expert group's judgments (using cardinal numbers) corresponding to the 26 items were classified as the following preference matrix.

Substituting the scoring data to perform the Pearson distance correlation operation row to row in pairs, a proximity matrix of the similarity measures (a 26 × 26 symmetric square matrix) was obtained as follows:

$$\mathbf{M}=\begin{bmatrix} 0.600 & 0.667 & 0.667 & 0.566 & 0.600 & 0.533 & 0.467 & 0.700 & 0.566 & 0.633 & 0.433 & 0.633 & 0.733 & 0.566 & 0.400 & 0.533 & 0.767 & 0.533 & 0.667 & 0.667 & 0.567 & 0.533 & 0.700 & 0.433 & 0.433 & 0.467 \\ 0.700 & 0.867 & 0.666 & 0.667 & 0.600 & 0.567 & 0.700 & 0.733 & 0.600 & 0.700 & 0.567 & 0.567 & 0.833 & 0.600 & 0.700 & 0.667 & 0.800 & 0.700 & 0.667 & 0.700 & 0.500 & 0.634 & 0.700 & 0.500 & 0.600 & 0.633 \\ 0.333 & 0.400 & 0.733 & 0.367 & 0.333 & 0.600 & 0.600 & 0.233 & 0.334 & 0.633 & 0.134 & 0.633 & 0.433 & 0.567 & 0.667 & 0.300 & 0.367 & 0.467 & 0.167 & 0.200 & 0.467 & 0.134 & 0.600 & 0.567 & 0.400 & 0.733 \\ 0.433 & 0.733 & 0.533 & 0.633 & 0.333 & 0.467 & 0.466 & 0.567 & 0.533 & 0.633 & 0.467 & 0.633 & 0.733 & 0.400 & 0.567 & 0.367 & 0.533 & 0.433 & 0.400 & 0.533 & 0.733 & 0.467 & 0.667 & 0.367 & 0.300 & 0.700 \\ 0.800 & 0.600 & 0.833 & 0.700 & 0.900 & 0.900 & 0.900 & 0.766 & 0.667 & 0.933 & 0.700 & 0.933 & 0.567 & 0.800 & 0.933 & 0.900 & 0.700 & 0.867 & 0.700 & 0.733 & 0.667 & 0.700 & 0.700 & 0.867 & 0.633 & 0.933 \\ 0.267 & 0.567 & 0.800 & 0.600 & 0.433 & 0.567 & 0.567 & 0.500 & 0.500 & 0.800 & 0.333 & 0.633 & 0.533 & 0.367 & 0.767 & 0.433 & 0.467 & 0.300 & 0.400 & 0.434 & 0.667 & 0.267 & 0.633 & 0.367 & 0.300 & 0.666 \end{bmatrix} \tag{13}$$

The resultant proximity matrix is a pairwise comparison of the global scoring relations derived from the similarity measures of the experts' assessments for the product samples. Taking advantage of the eigenvalue algorithms, a set of eigenvalues was derived as λ =

$$\mathbf{P}=\begin{bmatrix} 1.000 & 0.708 & 0.452 & 0.771 & 0.926 & 0.744 & 0.781 & 0.898 & 0.889 & 0.639 & 0.916 & 0.707 & 0.694 & 0.896 & 0.526 & 0.939 & 0.918 & 0.969 & 0.921 & 0.914 & 0.360 & 0.957 & 0.923 & 0.789 & 0.941 & 0.532 \\ 0.708 & 1.000 & 0.073 & 0.841 & 0.530 & 0.231 & 0.377 & 0.848 & 0.805 & 0.337 & 0.794 & 0.233 & 0.979 & 0.376 & 0.275 & 0.612 & 0.853 & 0.573 & 0.797 & 0.850 & 0.487 & 0.833 & 0.859 & 0.247 & 0.579 & 0.205 \\ 0.452 & 0.073 & 1.000 & 0.384 & 0.709 & 0.853 & 0.798 & 0.380 & 0.436 & 0.865 & 0.421 & 0.744 & 0.000 & 0.668 & 0.825 & 0.667 & 0.333 & 0.554 & 0.449 & 0.364 & 0.321 & 0.352 & 0.299 & 0.759 & 0.613 & 0.681 \\ 0.771 & 0.841 & 0.384 & 1.000 & 0.767 & 0.568 & 0.628 & 0.934 & 0.965 & 0.731 & 0.956 & 0.613 & 0.757 & 0.515 & 0.590 & 0.831 & 0.802 & 0.684 & 0.874 & 0.924 & 0.748 & 0.907 & 0.878 & 0.501 & 0.643 & 0.515 \\ 0.926 & 0.530 & 0.709 & 0.767 & 1.000 & 0.889 & 0.865 & 0.862 & 0.884 & 0.842 & 0.884 & 0.848 & 0.487 & 0.902 & 0.678 & 0.987 & 0.824 & 0.920 & 0.901 & 0.864 & 0.439 & 0.878 & 0.837 & 0.861 & 0.905 & 0.623 \\ 0.744 & 0.231 & 0.853 & 0.568 & 0.889 & 1.000 & 0.951 & 0.581 & 0.653 & 0.914 & 0.699 & 0.953 & 0.159 & 0.900 & 0.867 & 0.870 & 0.507 & 0.849 & 0.618 & 0.583 & 0.434 & 0.639 & 0.539 & 0.975 & 0.818 & 0.867 \\ 0.781 & 0.377 & 0.798 & 0.628 & 0.865 & 0.951 & 1.000 & 0.611 & 0.676 & 0.890 & 0.740 & 0.843 & 0.274 & 0.886 & 0.918 & 0.891 & 0.562 & 0.889 & 0.639 & 0.614 & 0.351 & 0.683 & 0.566 & 0.941 & 0.895 & 0.864 \\ 0.898 & 0.848 & 0.380 & 0.934 & 0.862 & 0.581 & 0.611 & 1.000 & 0.989 & 0.646 & 0.960 & 0.601 & 0.821 & 0.652 & 0.444 & 0.888 & 0.953 & 0.783 & 0.987 & 1.000 & 0.578 & 0.977 & 0.986 & 0.550 & 0.758 & 0.377 \\ 0.889 & 0.805 & 0.436 & 0.965 & 0.884 & 0.653 & 0.676 & 0.989 & 1.000 & 0.734 & 0.986 & 0.685 & 0.754 & 0.667 & 0.544 & 0.916 & 0.900 & 0.798 & 0.963 & 0.985 & 0.651 & 0.972 & 0.957 & 0.608 & 0.757 & 0.488 \\ 0.639 & 0.337 & 0.865 & 0.731 & 0.842 & 0.914 & 0.890 & 0.646 & 0.734 & 1.000 & 0.745 & 0.886 & 0.218 & 0.697 & 0.921 & 0.852 & 0.494 & 0.702 & 0.646 & 0.629 & 0.623 & 0.637 & 0.547 & 0.809 & 0.688 & 0.824 \\ 0.916 & 0.794 & 0.421 & 0.956 & 0.884 & 0.699 & 0.740 & 0.960 & 0.986 & 0.745 & 1.000 & 0.726 & 0.732 & 0.719 & 0.605 & 0.929 & 0.869 & 0.855 & 0.927 & 0.962 & 0.641 & 0.980 & 0.936 & 0.677 & 0.800 & 0.586 \\ 0.707 & 0.233 & 0.744 & 0.613 & 0.848 & 0.953 & 0.843 & 0.601 & 0.685 & 0.886 & 0.726 & 1.000 & 0.178 & 0.821 & 0.786 & 0.819 & 0.473 & 0.783 & 0.606 & 0.604 & 0.627 & 0.655 & 0.563 & 0.918 & 0.692 & 0.866 \\ 0.694 & 0.979 & 0.000 & 0.757 & 0.487 & 0.159 & 0.274 & 0.821 & 0.754 & 0.218 & 0.732 & 0.178 & 1.000 & 0.365 & 0.132 & 0.546 & 0.865 & 0.539 & 0.783 & 0.828 & 0.433 & 0.805 & 0.860 & 0.198 & 0.539 & 0.097 \\ 0.896 & 0.376 & 0.668 & 0.515 & 0.902 & 0.900 & 0.886 & 0.652 & 0.667 & 0.697 & 0.719 & 0.821 & 0.365 & 1.000 & 0.653 & 0.878 & 0.694 & 0.963 & 0.717 & 0.672 & 0.218 & 0.746 & 0.678 & 0.957 & 0.946 & 0.691 \\ 0.526 & 0.275 & 0.825 & 0.590 & 0.678 & 0.867 & 0.918 & 0.444 & 0.544 & 0.921 & 0.605 & 0.786 & 0.132 & 0.653 & 1.000 & 0.723 & 0.320 & 0.659 & 0.435 & 0.433 & 0.498 & 0.485 & 0.353 & 0.804 & 0.665 & 0.922 \\ 0.939 & 0.612 & 0.667 & 0.831 & 0.987 & 0.870 & 0.891 & 0.888 & 0.916 & 0.852 & 0.929 & 0.819 & 0.546 & 0.878 & 0.723 & 1.000 & 0.838 & 0.935 & 0.909 & 0.890 & 0.461 & 0.912 & 0.856 & 0.843 & 0.923 & 0.654 \\ 0.918 & 0.853 & 0.333 & 0.802 & 0.824 & 0.507 & 0.562 & 0.953 & 0.900 & 0.494 & 0.869 & 0.473 & 0.865 & 0.694 & 0.320 & 0.838 & 1.000 & 0.799 & 0.975 & 0.960 & 0.353 & 0.941 & 0.976 & 0.523 & 0.812 & 0.244 \\ 0.969 & 0.573 & 0.554 & 0.684 & 0.920 & 0.849 & 0.889 & 0.783 & 0.798 & 0.702 & 0.855 & 0.783 & 0.539 & 0.963 & 0.659 & 0.935 & 0.799 & 1.000 & 0.814 & 0.801 & 0.308 & 0.875 & 0.802 & 0.904 & 0.975 & 0.683 \\ 0.921 & 0.797 & 0.449 & 0.874 & 0.901 & 0.618 & 0.639 & 0.987 & 0.963 & 0.646 & 0.927 & 0.606 & 0.783 & 0.717 & 0.435 & 0.909 & 0.975 & 0.814 & 1.000 & 0.987 & 0.475 & 0.961 & 0.979 & 0.593 & 0.811 & 0.349 \\ 0.914 & 0.850 & 0.364 & 0.924 & 0.864 & 0.583 & 0.614 & 1.000 & 0.985 & 0.629 & 0.962 & 0.604 & 0.828 & 0.672 & 0.433 & 0.890 & 0.960 & 0.801 & 0.987 & 1.000 & 0.562 & 0.985 & 0.993 & 0.564 & 0.772 & 0.380 \\ 0.360 & 0.487 & 0.321 & 0.748 & 0.439 & 0.434 & 0.351 & 0.578 & 0.651 & 0.623 & 0.641 & 0.627 & 0.433 & 0.218 & 0.498 & 0.461 & 0.353 & 0.308 & 0.475 & 0.562 & 1.000 & 0.538 & 0.513 & 0.337 & 0.185 & 0.569 \\ 0.957 & 0.833 & 0.352 & 0.907 & 0.878 & 0.639 & 0.683 & 0.977 & 0.972 & 0.637 & 0.980 & 0.655 & 0.805 & 0.746 & 0.485 & 0.912 & 0.941 & 0.875 & 0.961 & 0.985 & 0.538 & 1.000 & 0.982 & 0.648 & 0.831 & 0.475 \\ 0.923 & 0.859 & 0.299 & 0.878 & 0.837 & 0.539 & 0.566 & 0.986 & 0.957 & 0.547 & 0.936 & 0.563 & 0.860 & 0.678 & 0.353 & 0.856 & 0.976 & 0.802 & 0.979 & 0.993 & 0.513 & 0.982 & 1.000 & 0.544 & 0.770 & 0.328 \\ 0.789 & 0.247 & 0.759 & 0.501 & 0.861 & 0.975 & 0.941 & 0.550 & 0.608 & 0.809 & 0.677 & 0.918 & 0.198 & 0.957 & 0.804 & 0.843 & 0.523 & 0.904 & 0.593 & 0.564 & 0.337 & 0.648 & 0.544 & 1.000 & 0.866 & 0.858 \\ 0.941 & 0.579 & 0.613 & 0.643 & 0.905 & 0.818 & 0.895 & 0.758 & 0.757 & 0.688 & 0.800 & 0.692 & 0.539 & 0.946 & 0.665 & 0.923 & 0.812 & 0.975 & 0.811 & 0.772 & 0.185 & 0.831 & 0.770 & 0.866 & 1.000 & 0.613 \\ 0.532 & 0.205 & 0.681 & 0.515 & 0.623 & 0.867 & 0.864 & 0.377 & 0.488 & 0.824 & 0.586 & 0.866 & 0.097 & 0.691 & 0.922 & 0.654 & 0.244 & 0.683 & 0.349 & 0.380 & 0.569 & 0.475 & 0.328 & 0.858 & 0.613 & 1.000 \end{bmatrix} \tag{14}$$

{18.907, 4.212, 1.576, 0.58, 0.514, 0.235, −0.003, −0.003, 0.001, −0.003, 0, −0.002, −0.002, 0, 0, −0.002, 0, 0, −0.002, −0.001, −0.001, −0.001, −0.001, −0.001, −0.001, −0.001}. The item weights represent the priority/importance of the principal diagonal elements within the proximity matrix, and can be determined by calculating the absolute values of the eigenvectors corresponding to the maximum eigenvalue. The larger the weight, the greater the respective element's unique positive contribution to all preference relations.

By calculating the absolute values of the eigenvectors and normalizing these eigenvectors corresponding to the maximum eigenvalue λ_{max} = 18.907, the item weight values were derived. According to the corresponding interval numbers given in Table 2, the weight values were converted into a set of weight rating scale variables, as shown in Appendix B. According to the results, the highest weights were given to items u_{11} (enjoyable-annoying), u_{14} (pleasant-unpleasant), u_{42} (supportive-obstructive), and u_{51} (valuable-inferior), while the lowest weight was given to item u_{24} (clear-confusing). As a whole, the dimensions of Efficiency and Dependability were much more important than that of Perspicuity in terms of the expert group's perspectives on the UX measure of computer mice. The results are rational as such interactive products mostly stress the pragmatic quality of the UX constructs. Further analysis of the results also revealed that the item weights, in substance, are consistent with the importance ratings derived from the expert interviews (see Appendix B).

Table 4
List of the derived fuzzy variables of ratings and weights.

Dimension	Item	Weight	Rating					
			Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Attractiveness (u_1)	enjoyable-annoying (u_{11})	R_7	R_5	R_5	R_3	R_3	R_6	R_5
	good-bad (u_{12})	R_5	R_4	R_5	R_5	R_5	R_7	R_5
	pleasing-unlikable (u_{13})	R_5	R_4	R_4	R_4	R_4	R_6	R_5
	pleasant-unpleasant (u_{14})	R_7	R_4	R_4	R_3	R_3	R_6	R_5
	attractive-unattractive (u_{15})	R_5	R_3	R_4	R_4	R_4	R_6	R_5
	friendly-unfriendly (u_{16})	R_6	R_6	R_5	R_3	R_4	R_6	R_5
Perspicuity (u_2)	comprehensible-incomprehensible (u_{21})	R_3	R_6	R_5	R_3	R_4	R_6	R_5
	easy to learn-difficult to learn (u_{22})	R_6	R_6	R_5	R_3	R_4	R_6	R_5
	simple-complicated (u_{23})	R_2	R_6	R_5	R_4	R_4	R_6	R_5
	clear-confusing (u_{24})	R_1	R_6	R_5	R_4	R_4	R_6	R_6
Efficiency (u_3)	fast-slow (u_{31})	R_6	R_6	R_5	R_4	R_5	R_6	R_5
	efficient-inefficient (u_{32})	R_6	R_6	R_5	R_3	R_4	R_6	R_5
	practical-impractical (u_{33})	R_6	R_5	R_5	R_4	R_4	R_6	R_5
	organized-cluttered (u_{34})	R_6	R_6	R_5	R_4	R_5	R_6	R_5
Dependability (u_4)	predictable-unpredictable (u_{41})	R_6	R_6	R_5	R_6	R_4	R_5	R_5
	supportive-obstructive (u_{42})	R_7	R_4	R_4	R_6	R_4	R_6	R_5
	secure-insecure (u_{43})	R_5	R_6	R_5	R_5	R_5	R_6	R_5
	meets expectations-does not meet expectations (u_{44})	R_6	R_5	R_5	R_6	R_4	R_6	R_5
Stimulation (u_5)	valuable-inferior (u_{51})	R_7	R_4	R_4	R_3	R_3	R_6	R_5
	exiting-boring (u_{52})	R_5	R_4	R_4	R_4	R_4	R_6	R_5
	interesting-not interesting (u_{53})	R_5	R_3	R_4	R_4	R_4	R_6	R_5
	motivating-non-motivating (u_{54})	R_6	R_4	R_4	R_3	R_4	R_6	R_5
Novelty (u_6)	creative-dull (u_{61})	R_2	R_3	R_5	R_5	R_4	R_6	R_5
	inventive-conventional (u_{62})	R_5	R_3	R_4	R_5	R_5	R_7	R_6
	leading edge-common (u_{63})	R_3	R_3	R_3	R_4	R_4	R_6	R_5
	innovative-conservative (u_{64})	R_3	R_3	R_4	R_5	R_4	R_7	R_6

4.5. UX measure for the selected product samples

Reliability was evaluated by assessing the internal consistency of the UEQ scales. According to the UX testing results, the statistics (means, standard deviations (S.D.), confidence intervals (C.I.), and Cronbach's alpha coefficients) of the user group's judgments with respect to each of the product samples were categorized, as shown in Appendix C. The high Cronbach's alpha values indicate good internal consistency of the items in the scales. Most single scales also showed high consistency values except the Dependability dimension for Sample 3. As a whole, the reliability of the questionnaires was acceptable. The means of the user group's judgments were then converted into rating variables according to the corresponding interval numbers given in Table 2. The derived fuzzy variables of ratings and weights are listed in Table 4.

By substituting the corresponding fuzzy numbers of the rating and weight variables into Eq. (4) to perform the aggregation operations, the resultant membership functions and their corresponding defuzzified fuzzy numbers were derived, as shown in Fig. 5. Then, the quantitative values of the membership grades, $\hat{\mu}_U(u_i)$, corresponding to each

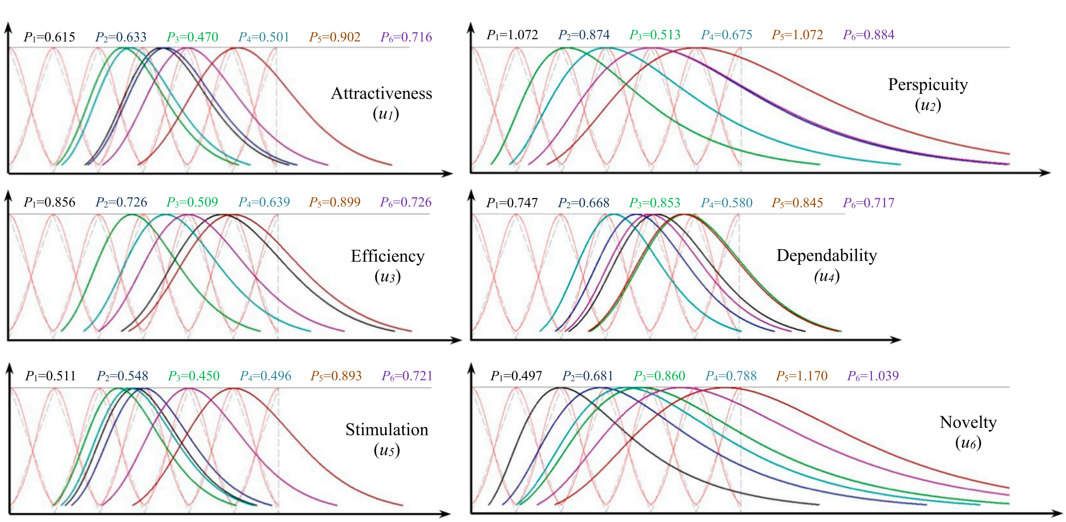

Fig. 5. Resultant membership functions and their defuzzified fuzzy numbers corresponding to each UX dimension.

Table 5
UXI results corresponding to the selected product samples.

		u_1	u_2	u_3	u_4	u_5	u_6	Sum.	UXI	Rank
Sample 1	$m(U_1)$	0.525	0.916	0.731	0.638	0.436	0.424	3.6700	1.0242	3
	$d(U_1)$	0.6919	0.2884	0.5823	0.6546	0.6849	0.6815	3.5834		
Sample 2	$m(U_2)$	0.541	0.746	0.620	0.571	0.468	0.582	3.5280	0.8877	4
	$d(U_2)$	0.6898	0.5667	0.6641	0.6830	0.6911	0.6796	3.9743		
Sample 3	$m(U_3)$	0.401	0.438	0.435	0.728	0.384	0.734	3.1200	0.8054	5
	$d(U_3)$	0.6734	0.6854	0.6847	0.5852	0.6660	0.5792	3.8739		
Sample 4	$m(U_4)$	0.428	0.576	0.546	0.495	0.424	0.673	3.1420	0.7739	6
	$d(U_4)$	0.6827	0.6815	0.6889	0.6931	0.6815	0.6320	4.0597		
Sample 5	$m(U_5)$	0.770	0.916	0.768	0.722	0.763	0.999	4.9380	1.9615	1
	$d(U_5)$	0.5393	0.2884	0.5417	0.5910	0.5476	0.0079	2.5159		
Sample 6	$m(U_6)$	0.611	0.755	0.620	0.612	0.616	0.887	4.1010	1.1469	2
	$d(U_6)$	0.6683	0.5568	0.6641	0.6678	0.6660	0.3527	3.5757		

product sample were obtained by further mapping the defuzzified numbers into the interval (0,1), as shown in Table 5.

Lastly, the UXIs corresponding to the selected product samples were derived by substituting the membership grade values into Eq. (12), as also shown in Table 5. According to the UXI results, the ranking of the product samples is $Sample5 > Sample6 > Sample1 > Sample2 > Sample3 > Sample4$. In terms of the user group's UX perceptions of the touch mice, the best example was Sample 5 (Microsoft Arc Touch Mouse) and the worst was Sample 4 (ATake Touch Mouse). The bar charts and benchmark comparison shown in Appendix D can also illustrate the results. This outcome is rational and credible as Sample 5 is a unique touch mouse developed by Microsoft for supporting Windows 8 desktop touch applications. Further analysis of the results indicates that Sample 1 (Logitech Zone Touch Mouse T400) had a high measure value for the Perspicuity dimension but relatively low values for both the Stimulation and Novelty dimensions, leading to its UXI being lower than that of Sample 6 (Logitech Ultrathin Touch Mouse T630). It is worth noting that the measure value of Sample 4 (ATake Touch Mouse) is higher than that of Sample 3 (Rapoo T6 Touch Mouse); however, the UXI of Sample 4 is lower than that of Sample 3. This reverse order is due to the entropy value of Sample 4 being higher than that of Sample 3 in terms of the UX measure. Further analysis of the raw data reveals that the users' responses to Sample 4 follow a central tendency, which implies a high fuzziness degree of the measure.

The above analysis results were derived from the empirical study concerning the episodic UX measures of using a set of touch mice. It is well known that a product should allow the intended user experiences before launching it into the market, and that the earlier we can evaluate user experience the more likely the product will be successful. As same as the implications of general UX evaluation studies, the analysis results can be expected to contribute to the early stage of a specific product design by providing designers with feedback on users' perceptions of the interactions that constitute qualities of using the product.

5. Discussion

In this paper, a psychometric UX model based on fuzzy measure approaches is proposed. Compared to existing UX models and conventional UEQ methods, the proposed model has distinct advantages in quantitative measures of UX. The theoretical and practical implications of the psychometric UX model are discussed in the following.

This study applied the User Experience Questionnaire (UEQ) to collect users' respondent data. In the reliability analysis results, the Cronbach's alpha value for the Dependability scale of Sample 3 was relatively low even though the questionnaire had an acceptable reliability as a whole (see Appendix C). Further analysis of the result revealed that the item-pairs 8–11, 8–17, 8–19, 11–17, 11–19, and 17–19 have lower correlation (0.19, 0.13, 0.14, 0.17, 0.22, 0.05, and 0.15, respectively) that yields the low Alpha coefficient. This is because the subjects have inconsistencies to interpret the 4 worded terms (unpredictable/predictable, obstructive/supportive, secure/not secure, and meets expectations/does not meet expectations) of the scale in terms of the UX responses to Sample 3. Although the UEQ has been recognized as a validated instrument which covers comprehensive UX dimensions measuring both classic usability aspects (efficiency, perspicuity, and dependability) and UX aspects (novelty and stimulation), it nevertheless has limitations for assessing the UX of various kinds of interactive products because different products aim at different dimensions of perceived experiences. To improve the UEQ strength, the proposed model prioritizes the 26 items with different weights for a specific product, for which the item weights are elicited from expert judgments toward the product. Distance-based optimization plays an important role in deriving criteria weights [83,84], while eigenvalues can be used for a covariance matrix to convert a set of observations of possibly correlated variables into a set of principal components [85]. The weighting method uses a proximity matrix derived from the distance correlation measures of experts' global scoring relations. The derived proximity matrix can be regarded as a covariance matrix of the standardized random variables, and has the properties of non-negativity, reflexivity, symmetry, and transitivity. Via the eigenvalue algorithms, we can derive a set of weights from the optimally weighted observed variables [81,82]. The weights corresponding to the UX items are elicited from the principal diagonal elements within the proximity matrix, and can reasonably reflect the respective item's unique positive contribution to the whole preference relations.

In many UX studies, respondents have been customarily asked in a questionnaire to indicate their appropriate choices from a set of self-report inventories. Such responses are fuzzy because the preference options often cannot be objectively and uniformly differentiated by all respondents [86]. The conventional UEQ method is based on the semantic differential (SD) format using a 7-point scale ranging in score from -3 to 3 to gather respondents' ratings for each perceptual item. Many researchers consider the psychometric rating scales as ordinal data rather than interval data since one cannot assume that respondents perceive all pairs of adjacent levels as equidistant. The difference or intensity of feeling/perception between two adjacent values is often ignored and mostly approximated to the closer one as the preference option; however, such value/option does not really reflect the respondent's preferences [87]. Moreover, respondents might be reluctant or unable to choose among a prefixed set of values. Although the visual analogue scale and fuzzy rating scale have flexible advantages over the SD scale, their use still has limitations, particularly the increased cognitive demand and the descriptive and inferential statistics [88,89]. Fuzzy numbers/intervals are better than crisp numbers as they catch the ambiguity intrinsic to human ratings or judgments [87]. The proposed model treats the 7-point ratings as fuzzy conversion scales described by continuous Gaussian membership functions (GMFs). As such, since the ratings are derived from the user group's judgments, using Gaussian fuzzy numbers (where the membership function is characterized by a normalized and symmetrically parameterized Gaussian function) can more flexibly reflect the statistical interpretation of the questionnaire response results (e.g., means, standard deviations, and confidence intervals) than using triangular or trapezoidal fuzzy numbers. These rating scales are defined respectively by fuzzy numbers (the GMFs), interval numbers (between the intersections of any two adjacent GMFs), and cardinal numbers (the center values of the GMFs) according to different α-cut levels. Differently defined numbers are used for different processes to establish priorities of preference relations, while simultaneously taking into account the intrinsic ambiguity associated with the UX responses.

Conventional UEQ method uses descriptive statistics (i.e., means, standard deviations, and confidence intervals) represented by bar charts and benchmark comparison to interpret the UX test results. Although the benchmark can help practitioners interpret scale results from UEQ evaluations, it does not distinguish between different product categories [90]. The bar charts and benchmark analysis are also difficult for UX practitioners to rank the product alternatives by using quantitative values (for example, the difference between Samples 3 and 4 of the case study shown in Appendix D). In the literature, UX measures have mostly been conducted in association with statistical techniques, such as analysis of variance (ANOVA), factor analysis, and correlation and regression analysis [91,92]. The simplest quantitative model is linear feature-based, with a weighted sum of different UX constructs and coefficients estimated using statistical analysis, such as multiple regression analysis and maximum likelihood estimation. For example, Park et al. [29] applied five modeling techniques to quantify UX and conducted a case study with a tablet PC through 13 designed tasks to validate the resultant models. In their study, three compensatory models (simple linear, polynomial, and S-shaped value) and two non-compensatory models (conjunctive and disjunctive) were used, and all models were transformed into linear relationships in order to estimate coefficients through multiple regression analysis. They concluded that both compensatory and non-compensatory models have good performance in measuring UX. However, the 22 dimensions in their case study for evaluating UX may require further validation and the linear quantification model for integrating multiple elements into a single value could be questionable. Moreover, a multiple regression model has limitations as it imprecisely assumes that all predictors are linearly related to each other, and also has a statistical limitation on the number of explanatory variables [93,94]. Previous research has also indicated that such UX responses do not follow simple characterizations of linearity, but rather are fuzzy and vague in nature [95,96]. UX measures involve complex human perceptual interpretations of experiential responses, which can manifest as a non-linear pattern due to uncertain, imprecise, or incomplete data caused by human error, recording error, or arbitrary guesses. Based on the validated items of the UEQ, the proposed model uses fuzzy measure approaches to estimate UX quantitatively. In this model, the respondents' ratings and item weights are converted into fuzzy numbers and aggregated by means of the aggregation operations. The resultant fuzzy numbers are then defuzzified to derive a set of quantitative values for the fuzzy measures of the product samples. This novel aggregation with continuous α-cuts is considered an extension principle-based method [97], which enables fuzzy numbers to be aggregated through the arithmetic operations on closed intervals. The defuzzification operation for the resultant fuzzy numbers can also provide objective quantitative values derived from the respondents' subjective judgments.

A quantification model usually integrates multiple elements into a single value. Many quantitative UX models have applied multi-attribute utility theory (MAUT) methods to synthesize user preference information into a single index. However, in MAUT, a multi-attribute utility function describes the respondents' preferences, which is a linear combination of the local utility values. Indeed, Zenebe et al. [98] argued that fuzzy models are more effective than traditional MAUT approaches for representing and reasoning item features and user preferences which involve uncertainty due to subjectivity, imprecision, and vagueness. Based on the UEQ and fuzzy measure approaches, this study developed a user experience index (UXI) as a metric for assessing UX quality quantitatively. The UXI is defined as the ratio of the normalized fuzzy measure of the UX set to its normalized fuzzy entropy. The fuzzy measure is used to derive the degree of the utility of preference information, whereas the fuzzy entropy is to mediate the effect of fuzziness for the UX measure. In the UXI measure, the membership grade is a crisp number converted from the resultant fuzzy set/number through the aggregation of fuzzy rating and fuzzy weight variables with continuous α-cuts and the COG defuzzification operations. Nevertheless, like any other type of questionnaire survey, the UEQ can suffer from response bias, such as central tendency bias, acquiescence bias, or social desirability bias. Fortunately, the UEQ is based on the validated semantic differential (SD) format, measuring either a positive or negative response to a UX preference. Moreover, a well-established SD-based questionnaire can reduce acquiescence bias, which occurs when respondents to a survey tend to agree with all the questions or indicate a positive connotation [99]. The proposed UXI can also reduce the influence of central tendency bias, as evidenced in the empirical study result. This is mainly due to the utilization of fuzzy entropy, which can not only indicate the fuzziness degree of the UX measure but can also mitigate the impact of central tendency bias caused by respondents who tend to avoid using extreme ends of the rating scale. As a whole, the proposed model allows for the incorporation of unquantifiable UX information, incomplete priority information, non-obtainable bias information, and partially ignorant facts on preference options into a holistic index. Hence, this psychometric UX model is capable of capturing users' ambiguous appraisals and is valid for measuring the UX quality of interactive products, which are helpful for designers to create meaningful experiences with users and the products they use.

6. Conclusions

UX-related methods have emerged within different research streams. This study aimed at implementing the psychological measures of UX via a mathematical model. In this paper, a psychometric UX model based on fuzzy measure approaches was presented, the purpose of which was to develop a metric for quantitative measures of UX through a user experience index (UXI). The UEQ was employed as a psychometric instrument to collect users' rating data, while the item weights were elicited from a proximity matrix of experts' preference relations using the eigenvalue algorithms. Both the rating and weight variables are converted into Gaussian fuzzy numbers and aggregated by means of the aggregation method with continuous α-cuts. The resultant fuzzy numbers are then defuzzified to derive a set of quantitative values as membership grades for the fuzzy measure and fuzzy entropy operations. The developed UXI was confirmed to be a valid metric for measuring the desirable degree of product UX. The empirical study result also verified the flexibility and feasibility of the proposed UX model.

In conclusion, this study contributes to our knowledge by using the UEQ associated with fuzzy measure approaches in UX research areas. It also introduces a valid index for evaluators to assess the UX quality of interactive products. UX broadly refers to users' emotions, beliefs, preferences, perceptions, behaviors and so on, and describes their physical and psychological responses that result from the use of a product, system, or service in a particular context of use. Further research could focus on developing a physiometric UX system for measuring users' experiential responses to a product by means of psycho-physiological measurement technologies such as heart rate and blood pressure, eye tracking, electromyography (EMG), electroencephalography (EEG), event-related potential (ERP), galvanic skin response (GSR), respiration amplitude/respiration rate (RespAmp/RespRate), and functional magnetic resonance imaging (fMRI).

Acknowledgement

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Appendix A. User experience questionnaire (UEQ) for the survey of touch mice

Demographic questions:

1. What is your gender? ☐ Male ☐ Female
2. What is your age? ____ years old
3. Are you right-handed or left-handed? ☐ Right-handed ☐ Left-handed

Please make your evaluation now.

For the assessment of the product, please fill out the following questionnaire. The questionnaire consists of pairs of contrasting attributes that may apply to the product. The circles between the attributes represent gradations between the opposites. You can express your agreement with the attributes by ticking the circle that most closely reflects your impression.

This response would mean that you rate the application as more attractive than unattractive.

Please decide spontaneously. Don't think too long about your decision to make sure that you convey your original impression.

Sometimes you may not be completely sure about your agreement with a particular attribute or you may find that the attribute does not apply completely to the particular product. Nevertheless, please tick a circle in every line.

It is your personal opinion that counts. Please remember: there is no wrong or right answer!

Please assess the product now by ticking one circle per line.

	1	2	3	4	5	6	7		
1. *What do you think about this touch mouse?*									
annoying	○	○	○	○	○	○	○	enjoyable	1
2. *What do you think about using this touch mouse?*									
not understandable	○	○	○	○	○	○	○	understandable	2
3. *Is the design of this touch mouse creative or dull?*									
creative	○	○	○	○	○	○	○	dull	3
4. *What do you think about learning how to use this touch mouse?*									
easy to learn	○	○	○	○	○	○	○	difficult to learn	4
5. *Do you feel likely or unlikely to further using this touch mouse?*									
valuable	○	○	○	○	○	○	○	inferior	5
6. *Is it exciting or boring to use this touch mouse?*									
boring	○	○	○	○	○	○	○	exciting	6
7. *Is it interesting to use this touch mouse?*									
not interesting	○	○	○	○	○	○	○	interesting	7
8. *Is the interaction with this touch mouse predictable or unpredictable?*									
unpredictable	○	○	○	○	○	○	○	predictable	8
9. *Is it possible to use this touch mouse quickly?*									
fast	○	○	○	○	○	○	○	slow	9
10. *Do you think the design of this touch mouse is inventive or conventional?*									
inventive	○	○	○	○	○	○	○	conventional	10
11. *While using this touch mouse, do you feel in control of the interaction?*									
obstructive	○	○	○	○	○	○	○	supportive	11
12. *What do you think about this touch mouse?*									
good	○	○	○	○	○	○	○	bad	12
13. *What do you think about getting familiar with this touch mouse?*									
complicated	○	○	○	○	○	○	○	easy	13
14. *What do you think about this touch mouse?*									
unlikable	○	○	○	○	○	○	○	pleasing	14
15. *Do you think the design of this touch mouse is usual or leading-edge?*									
usual	○	○	○	○	○	○	○	leading-edge	15

16. *What do you think about this touch mouse?*									
unpleasant	○	○	○	○	○	○	○	pleasant	16
17. *Is the interaction with this touch mouse secure or insecure?*									
secure	○	○	○	○	○	○	○	not secure	17
18. *Do you feel motivated or non-motivating to further use this touch mouse?*									
motivating	○	○	○	○	○	○	○	demotivating	18
19. *While using this touch mouse, do you feel in control of the interaction?*									
meets expectations	○	○	○	○	○	○	○	does not meet expectations	19
20. *Is it possible to use this touch mouse efficiently?*									
inefficient	○	○	○	○	○	○	○	efficient	20
21. *What do you think about using this touch mouse?*									
clear	○	○	○	○	○	○	○	confusing	21
22. *What do you think about the user interface of this touch mouse?*									
impractical	○	○	○	○	○	○	○	practical	22
23. *What do you think about the user interface design of this touch mouse?*									
organized	○	○	○	○	○	○	○	cluttered	23
24. *What do you think about this touch mouse?*									
attractive	○	○	○	○	○	○	○	unattractive	24
25. *Do you think this touch mouse is friendly or unfriendly?*									
friendly	○	○	○	○	○	○	○	unfriendly	25
26. *Is the design of this touch mouse innovative or conservative?*									
conservative	○	○	○	○	○	○	○	innovative	26

Appendix B. List of the item weights derived from the experts' assessment

Item		Eigenvector	Normalization	Interval	R.S.	Expert's rating (levels of importance)					
						Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Mean
1	u_{11}	0.219	0.928	(0.9165, 1]	R_7	6	7	6	7	7	0.933
2	u_{21}	0.161	0.330	[0.25, 0.4165)	R_3	4	2	3	2	4	0.333
3	u_{61}	0.144	0.155	[0.0835, 0.25)	R_2	2	1	2	2	3	0.167
4	u_{22}	0.202	0.753	(0.75, 0.9165]	R_6	5	6	5	6	6	0.767
5	u_{51}	0.222	0.959	(0.9165, 1]	R_7	7	6	7	6	7	0.933
6	u_{52}	0.194	0.670	(0.5835, 0.75]	R_5	5	4	5	5	6	0.667
7	u_{53}	0.199	0.722	(0.5835, 0.75]	R_5	5	6	5	6	5	0.733
8	u_{41}	0.211	0.845	(0.75, 0.9165]	R_6	5	7	6	7	5	0.833
9	u_{31}	0.217	0.907	(0.75, 0.9165]	R_6	6	7	6	7	6	0.900
10	u_{62}	0.191	0.639	(0.5835, 0.75]	R_5	5	4	3	5	6	0.600
11	u_{42}	0.221	0.948	(0.9165, 1]	R_7	6	7	6	7	7	0.933
12	u_{12}	0.189	0.619	(0.5835, 0.75]	R_5	3	5	5	5	6	0.633
13	u_{23}	0.148	0.196	[0.0835, 0.25)	R_2	2	2	3	2	2	0.200
14	u_{13}	0.198	0.711	(0.5835, 0.75]	R_5	4	6	5	5	7	0.733
15	u_{63}	0.165	0.371	[0.25, 0.4165)	R_3	4	1	3	3	5	0.367
16	u_{14}	0.226,	1.000	(0.9165, 1]	R_7	6	7	7	7	7	0.967
17	u_{43}	0.199	0.722	(0.5835, 0.75]	R_5	5	6	5	5	6	0.733
18	u_{54}	0.215	0.887	(0.75, 0.9165]	R_6	6	6	7	6	6	0.867
19	u_{44}	0.212	0.856	(0.75, 0.9165]	R_6	6	5	6	7	7	0.867
20	u_{32}	0.212	0.856	(0.75, 0.9165]	R_6	5	5	6	7	7	0.833
21	u_{24}	0.129	0.000	[0, 0.0835)	R_1	2	2	1	1	1	0.067
22	u_{33}	0.217	0.907	(0.75, 0.9165]	R_6	5	6	7	7	7	0.900
23	u_{34}	0.206	0.794	(0.75, 0.9165]	R_6	6	5	5	6	7	0.800
24	u_{15}	0.191	0.639	(0.5835, 0.75]	R_5	5	5	4	5	5	0.633
25	u_{16}	0.209	0.825	(0.75, 0.9165]	R_6	5	6	6	6	7	0.833
26	u_{64}	0.157	0.289	[0.25, 0.4165)	R_3	4	2	1	3	4	0.300

* Items 3 (u_{61}), 4 (u_{22}), 5 (u_{51}), 9 (u_{31}), 10 (u_{62}), 12 (u_{12}), 17 (u_{43}), 18 (u_{54}), 19 (u_{44}), 21 (u_{24}), 23 (u_{34}), 24 (u_{15}), and 25 (u_{16}) are negative worded terms.

* Importance rating (levels of importance):

1: Very low importance (0) 2: Low importance (0.167) 3: Moderately low importance (0.333) 4: Medium importance (0.5)

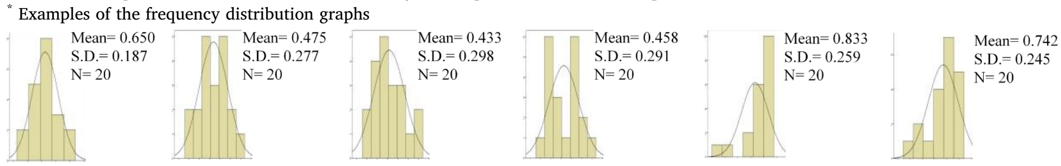
5: Moderately high importance (0.667) 6: High importance (0.833) 7: Very high importance (1)

Appendix C. List of the statistics derived from the users' assessment results

Item		Sample 1 Mean S.D.	C.I.	R.S.	Sample 2 Mean S.D.	C.I.	R.S.	Sample 3 Mean S.D.	C.I.	R.S.	Sample 4 Mean S.D.	C.I.	R.S.	Sample 5 Mean S.D.	C.I.	R.S.	Sample 6 Mean S.D.	C.I.	R.S.
1	u_{11}	0.650	0.568	R_5	0.600	0.474	R_5	0.342	0.193	R_3	0.383	0.228	R_3	0.817	0.706	R_6	0.692	0.577	R_5
		0.187	0.732		0.288	0.726		0.340	0.491		0.355	0.539		0.253	0.928		0.261	0.806	
2	u_{21}	0.825	0.735	R_6	0.600	0.459	R_5	0.392	0.243	R_3	0.567	0.407	R_4	0.783	0.653	R_6	0.742	0.637	R_5
		0.206	0.915		0.322	0.741		0.339	0.540		0.364	0.726		0.297	0.913		0.239	0.846	
3	u_{61}	0.383	0.269	R_3	0.625	0.540	R_5	0.600	0.463	R_5	0.467	0.336	R_4	0.908	0.844	R_6	0.750	0.640	R_5
		0.260	0.497		0.194	0.710		0.313	0.737		0.299	0.598		0.148	0.973		0.251	0.860	
4	u_{22}	0.808	0.689	R_6	0.667	0.544	R_5	0.408	0.265	R_3	0.550	0.449	R_4	0.833	0.720	R_6	0.733	0.637	R_5
		0.272	0.927		0.281	0.790		0.327	0.551		0.230	0.651		0.259	0.947		0.219	0.829	
5	u_{51}	0.500	0.402	R_4	0.558	0.430	R_4	0.400	0.269	R_3	0.408	0.254	R_3	0.858	0.790	R_6	0.742	0.645	R_5
		0.223	0.598		0.293	0.687		0.298	0.531		0.352	0.563		0.156	0.927		0.219	0.838	
6	u_{52}	0.425	0.296	R_4	0.467	0.362	R_4	0.458	0.338	R_4	0.458	0.345	R_4	0.858	0.794	R_6	0.700	0.592	R_5
		0.294	0.554		0.239	0.572		0.275	0.579		0.259	0.572		0.146	0.922		0.245	0.808	
7	u_{53}	0.392	0.263	R_3	0.475	0.354	R_4	0.475	0.342	R_4	0.417	0.266	R_4	0.858	0.772	R_6	0.683	0.565	R_5
		0.293	0.520		0.277	0.596		0.302	0.608		0.344	0.567		0.197	0.945		0.270	0.802	
8	u_{41}	0.792	0.707	R_6	0.642	0.503	R_5	0.758	0.659	R_6	0.567	0.420	R_4	0.683	0.563	R_5	0.700	0.580	R_5
		0.194	0.877		0.317	0.780		0.226	0.857		0.335	0.714		0.275	0.804		0.274	0.820	
9	u_{31}	0.883	0.808	R_6	0.692	0.555	R_5	0.417	0.284	R_4	0.717	0.610	R_5	0.850	0.750	R_6	0.733	0.629	R_5
		0.172	0.959		0.312	0.828		0.303	0.550		0.242	0.823		0.229	0.950		0.238	0.838	
10	u_{62}	0.333	0.197	R_3	0.583	0.490	R_4	0.725	0.608	R_5	0.683	0.556	R_5	0.942	0.899	R_7	0.808	0.719	R_6
		0.311	0.469		0.213	0.677		0.266	0.842		0.291	0.811		0.098	0.985		0.204	0.898	
11	u_{42}	0.550	0.452	R_4	0.442	0.313	R_4	0.767	0.671	R_6	0.450	0.300	R_4	0.775	0.656	R_6	0.650	0.532	R_5
		0.224	0.648		0.293	0.570		0.219	0.863		0.342	0.600		0.272	0.894		0.270	0.768	
12	u_{12}	0.425	0.303	R_4	0.592	0.490	R_5	0.750	0.645	R_5	0.600	0.485	R_5	0.958	0.918	R_7	0.750	0.663	R_5
		0.278	0.547		0.232	0.694		0.239	0.855		0.262	0.715		0.092	0.999		0.199	0.837	
13	u_{23}	0.900	0.824	R_6	0.708	0.588	R_5	0.417	0.295	R_4	0.567	0.468	R_4	0.758	0.630	R_6	0.683	0.558	R_5
		0.174	0.976		0.275	0.829		0.278	0.539		0.226	0.666		0.294	0.887		0.286	0.809	
14	u_{13}	0.525	0.401	R_4	0.517	0.425	R_4	0.450	0.316	R_4	0.417	0.264	R_4	0.817	0.732	R_6	0.658	0.556	R_5
		0.282	0.649		0.209	0.608		0.306	0.584		0.348	0.569		0.194	0.902		0.232	0.760	
15	u_{63}	0.392	0.243	R_3	0.408	0.269	R_3	0.583	0.466	R_4	0.500	0.375	R_4	0.892	0.816	R_6	0.692	0.577	R_5
		0.339	0.540		0.317	0.547		0.268	0.701		0.286	0.625		0.173	0.968		0.261	0.806	
16	u_{14}	0.558	0.460	R_4	0.500	0.384	R_4	0.367	0.229	R_3	0.383	0.247	R_3	0.808	0.710	R_6	0.683	0.578	R_5
		0.225	0.657		0.265	0.616		0.313	0.504		0.311	0.520		0.225	0.907		0.241	0.789	
17	u_{43}	0.858	0.782	R_6	0.642	0.495	R_5	0.633	0.540	R_5	0.633	0.494	R_5	0.792	0.686	R_6	0.750	0.651	R_5
		0.173	0.934		0.335	0.788		0.214	0.727		0.318	0.773		0.241	0.897		0.226	0.849	
18	u_{54}	0.442	0.313	R_4	0.458	0.333	R_4	0.400	0.265	R_3	0.458	0.331	R_4	0.817	0.716	R_6	0.683	0.572	R_5
		0.293	0.570		0.285	0.583		0.308	0.535		0.291	0.586		0.229	0.917		0.253	0.794	
19	u_{44}	0.750	0.657	R_5	0.592	0.443	R_5	0.775	0.679	R_6	0.458	0.312	R_4	0.808	0.689	R_6	0.742	0.634	R_5
		0.213	0.843		0.340	0.741		0.218	0.871		0.333	0.604		0.272	0.927		0.245	0.849	
20	u_{32}	0.800	0.690	R_6	0.692	0.561	R_5	0.400	0.263	R_3	0.483	0.330	R_4	0.792	0.691	R_6	0.717	0.593	R_5
		0.251	0.910		0.298	0.822		0.313	0.537		0.350	0.637		0.229	0.892		0.281	0.840	
21	u_{24}	0.850	0.765	R_6	0.692	0.570	R_5	0.500	0.348	R_4	0.508	0.401	R_4	0.808	0.702	R_6	0.758	0.651	R_6
		0.194	0.935		0.277	0.813		0.346	0.652		0.245	0.616		0.243	0.915		0.245	0.866	
22	u_{33}	0.742	0.629	R_5	0.658	0.541	R_5	0.433	0.294	R_4	0.567	0.414	R_4	0.867	0.797	R_6	0.675	0.560	R_5
		0.256	0.854		0.268	0.776		0.317	0.572		0.348	0.719		0.159	0.936		0.262	0.790	
23	u_{34}	0.767	0.680	R_6	0.725	0.624	R_5	0.517	0.377	R_4	0.658	0.549	R_5	0.850	0.772	R_6	0.708	0.597	R_5
		0.198	0.853		0.231	0.826		0.319	0.657		0.251	0.768		0.179	0.928		0.253	0.819	
24	u_{15}	0.375	0.248	R_3	0.533	0.411	R_4	0.433	0.303	R_4	0.467	0.333	R_4	0.883	0.820	R_6	0.675	0.549	R_5
		0.291	0.502		0.279	0.656		0.298	0.564		0.304	0.600		0.144	0.946		0.289	0.801	
25	u_{16}	0.783	0.701	R_6	0.708	0.583	R_5	0.392	0.257	R_3	0.575	0.436	R_4	0.900	0.827	R_6	0.725	0.608	R_5
		0.188	0.866		0.285	0.833		0.307	0.526		0.317	0.714		0.166	0.973		0.266	0.842	
26	u_{64}	0.317	0.177	R_3	0.475	0.351	R_4	0.717	0.628	R_5	0.567	0.440	R_4	0.933	0.884	R_7	0.767	0.660	R_6
		0.319	0.457		0.282	0.599		0.203	0.806		0.288	0.693		0.113	0.983		0.244	0.874	
Cronbach's alpha		0.916			0.945			0.937			0.954			0.958			0.962		
		Attractiveness: 0.79			Attractiveness: 0.90			Attractiveness: 0.93			Attractiveness: 0.88			Attractiveness: 0.82			Attractiveness: 0.92		
		Perspicuity: 0.82			Perspicuity: 0.83			Perspicuity: 0.87			Perspicuity: 0.68			Perspicuity: 0.95			Perspicuity: 0.92		
		Efficiency: 0.72			Efficiency: 0.90			Efficiency: 0.80			Efficiency: 0.83			Efficiency: 0.72			Efficiency: 0.88		
		Dependability: 0.83			Dependability: 0.79			*Dependability: 0.41*			Dependability: 0.85			Dependability: 0.92			Dependability: 0.83		
		Stimulation: 0.89			Stimulation: 0.92			Stimulation: 0.84			Stimulation: 0.94			Stimulation: 0.74			Stimulation: 0.98		
		Novelty: 0.89			Novelty: 0.82			Novelty: 0.88			Novelty: 0.89			Novelty: 0.81			Novelty: 0.94		

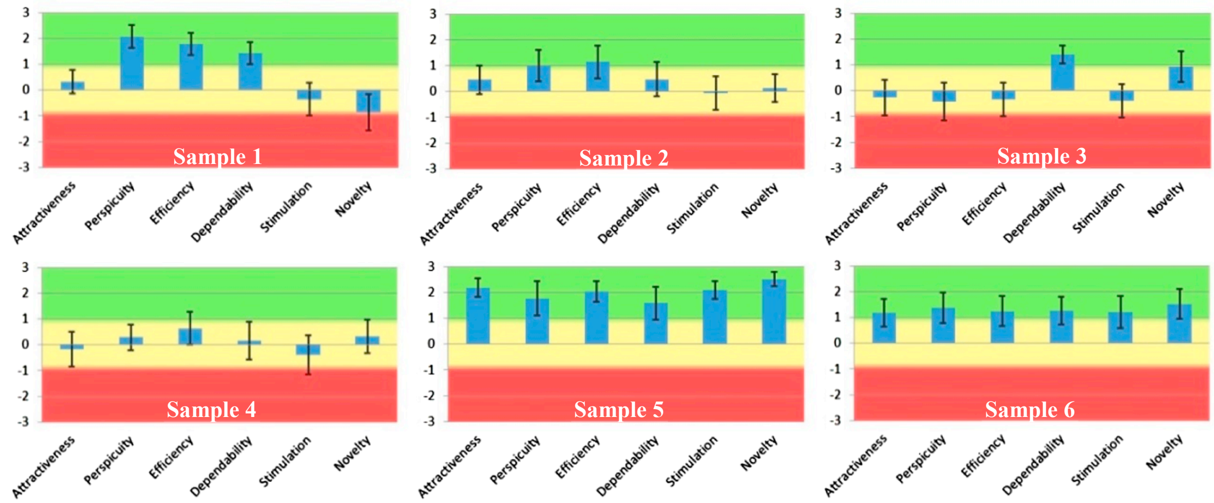
* The Cronbach's alpha values indicate that the reliability of the questionnaires was acceptable.

* Examples of the frequency distribution graphs

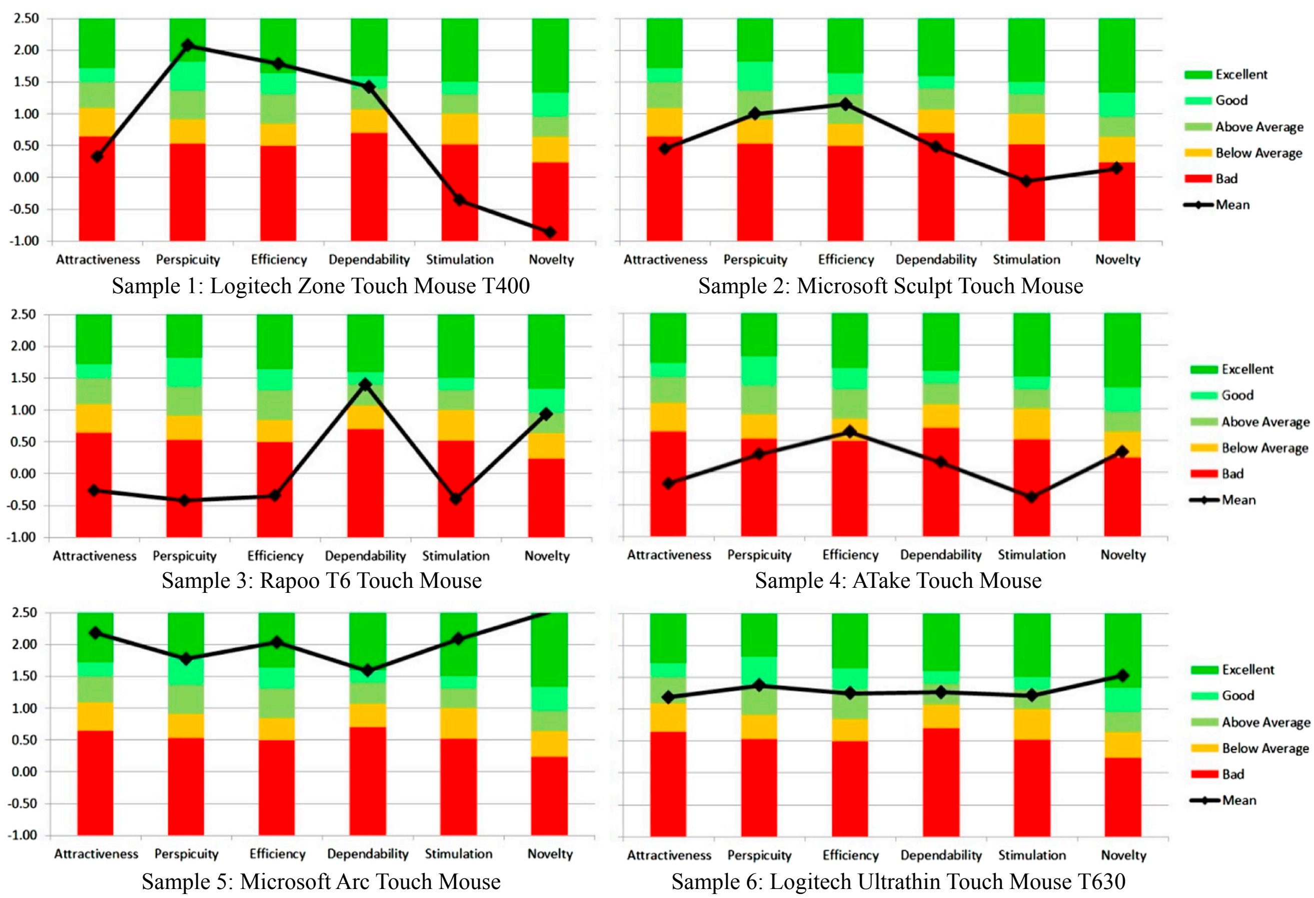


Sample 1 Item 1 (u_{11}) | Sample 2 Item 7 (u_{53}) | Sample 3 Item 24 (u_{15}) | Sample 4 Item 18 (u_{54}) | Sample 5 Item 4 (u_{22}) | Sample 6 Item 19 (u_{44})

Appendix D. Bar charts and benchmark comparison results derived from the UEQ data analysis tool and benchmark data set



(a) Bar charts with 5% confidence intervals for the scale means



(b) Benchmark comparison for the 6 product samples

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