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Relationship between overall difference decision and electronic tongue: Discrimination of civet coffee

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ABSTRACT

This paper demonstrates a new approach to relate electronic tongue (E-tongue) to human perception for fine quality of beverage. Six civet, one weasel and one non-civet coffees were chosen as the testing platform. The sensory test based on the overall difference method by pair comparison followed by sureness-rating tasks was divided into three experiments. In each, 12–14 consumers were asked to express differences in six pairs of hot brew coffee samples on a four-point scale. The results were analyzed by the Multi-Dimensional Scaling (MDS) analysis. An in-house electronic tongue based on cyclic voltammetry and the Principal Component Analysis (PCA) was applied to measure the coffee samples, alongside the panel test. The relationship between PCA and MDS solutions was obtained by Generalized Procrustes Analysis (GPA), which reveals a strong correlation between E-tongue and human perception. Both were able to identify differences between all coffee samples from different sources.

1. Introduction

Deliciousness of food may be assessed mainly through human senses of smell and taste whereas sight, hearing and touch can create appreciation of food that may increase the feeling of deliciousness. Odor and taste are undeniably the two most crucial factors in determining the deliciousness. To date, with the advances of science and sensor technology, electronic noses (E-nose) (Gardner and Barlett, 1994) and E-tongue (Di Natale et al., 1996; Otto and Thomas, 1985; Toko, 1996; Winquist et al., 1997) offer promising analytical instrument as a taste sensor and an odor sensor, respectively. The concept of both devices does not rely on discrimination of chemical constituents, but focuses on the recognition of the odor or taste itself via some quantitative expression (Lopetcharat and McDaniel, 2005; Toko, 1996). Both instruments consist of a sensing array, a measuring system and a multivariate analysis. E-nose has long been applied to examine food quality (Gardner and Barlett, 1994; Loutfi et al., 2015). Applications of E-tongue for food quality assessment (Ha et al., 2015; Vlasov et al., 2002) are rather more recent and emerging as a promising tool, which have been demonstrated on many food stuffs and beverages, such as coffee (Buratti et al., 2015; Domínguez et al., 2014; Várvölgyi et al., 2015), tea (Bhattacharyya et al., 2012; Bhondekar et al., 2010), milk (Bougrini et al., 2014), drinking water (Winquist et al., 2011), beers (Rudnitskaya et al., 2009), wines (Cetó et al., 2015; Legin et al., 2003; Ouyang et al., 2014), olive oil (Dias et al., 2016) and flesh food (Haddi et al., 2015; Rudnitskaya et al., 2002). Despite numeral studies on artificial sensory systems, a question remains on their ability to match human perception. Real food dishes, which comprise many natural substances, mixing and suaveness of the tastes and odors, pose an interesting challenge for such systems.

To compare artificial sensory system, such as E-tongue, with human perception, two approaches have been widely applied. One is to relate quantitatively specific chemicals for a particular food attribute to measurements by an E-tongue (Legin et al., 2003; Toko, 1996; Várvölgyi et al., 2015; Yang et al., 2013). Owing to either the complexity of chemical constituents in food and their possible

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Abbreviation

A	Arabica
ANN	Artificial Neural Network
Ag	silver
AgCl	silver chloride
ANOVA	Analysis of Variance
C	Civet
Ch	Doichang Thailand
Cg	caged
Com	commercial grade
CV	cyclic voltammertic
E-nose	electronic nose
E-tongue	electronic tongue
Fr	free-range
GPA	Generalized Procrustes Analysis
I	Indonesia
MDS	multi-dimensional scaling
N	normal
PC	principal component
PCs	principle components
PCA	Principal Component Analysis
PLS	Partial Least Squares
Pt	platinum
Pure	high purity
R	Robusta
SMACOF	Scaling by Majorizing A Convex Function
SVM	supported vector machine
T	Thailand
Tg	Doitung Thailand
V	Vietnam
W	Weasel
w.b.	wet basis

interactions or the lack of information on the specific chemicals, this approach is not often applicable. The other approach is based on a sensory test with either an expert panel or a group of consumers, which relies on a questionnaire with number scoring tasks on particular or overall attributes of food samples (Cetó et al., 2015; Dias et al., 2016; Legin et al., 2003; Ouyang et al., 2014; Rudnitskaya et al., 2009; Várvölgyi et al., 2015). The relationship between the E-tongue outputs and certain food attributes may be achieved by a combination of various statistical analyses, such as Principal Component Analysis (PCA), Partial Least Squares (PLS), Supported Vector Machine (SVM) and Artificial Neural Network (ANN).

Upon judging fine qualities of food stuffs in most cases, consumers are aware when products are different, but they usually have a hard time to describe what make those differences. In these situations, when any specific characteristics that differentiate samples from each other are not known, or obtaining reliable descriptors is not possible, asking consumers to judge the overall difference between the samples become an effective and appropriate task to gauge the perception of consumers. To gain information regarding how different products are, many tasks may be used, e.g. sorting, mapping, direct rating of overall difference, pair-comparison (Lawless and Heymann, 1999). Pair-comparison tasks are more suitable for a few products with a carry-over effect than evaluation tasks involving many independent samples, due to possible memory loss (Lau et al., 2004). In the latter case, the MDS analysis are usually performed (Lawless and Heymann, 1999) to unfold the perceptual space of a product set, whereby small distances indicate more similarity and large distances indicates less similarity (Tang and Heymann, 2002). A proximity/distance matrix, or a square matrix indicating the level of similarity/dissimilarity between a series of samples, is the input for the MDS analysis. MDS algorithms are designed to minimize the difference between the disparity matrix created from models (written specifically for specific algorithms) and the distance matrix obtained from the actual data set.

GPA is a mathematical technique commonly used in consumer studies to investigate the similarities and differences of multiple data sets and maximizes the correlations between structures by creating new dimensions that captures correlations between the structures (Lopetcharat and McDaniel, 2005). This method allows one to study the relationship between very different measurements such as E-tongue and consumer's evaluation of overall differences without a complete set of pairings for all the samples.

Coffee is a delicate beverage in which its aroma and taste are sensitive for consumer acceptance. Coffee beans from civet cat (Asian palm civet, *Paradoxurus hermaphrodites*, toddy cat) are prepared from coffee berries that went through digestive tract of civet cats before further processes, such as drying, dehulling and roasting. Partial digestion and fermentation inside civet cat's digestive tract of the beans provide aromatic and low bitterness cup of coffee (Ali et al., 2012). The civet cat coffee is becoming popular and very expensive due to its exotic process in producing civet coffee as well as its distingue taste and aroma. In this study, the civet cat coffee from different sources was selected to test a performance of in-house developed E-tongue along with normal coffee.

Therefore, an information from investigation of the differentiated ability of human and E-tongue on coffee samples from different source of processing, location and variety of beans as well as their relationship will be useful tool for quality control to coffee industry. The objectives of this study are two folds. One is to assess the performance of the in-house developed cyclic voltammertic E-tongue in comparison to human perception via the overall-difference rating from pair-comparison tasks. The second is to investigate similarities and differences amongst the eight coffee types (Table 1) by comparing civet and non-civet coffee, different feeding conditions (caged *vs*. free-range), Thai civet coffee from the different geographical area (Doitung *vs.* Doichang), different countries (Thai *vs*. Vietnam *vs*. Indonesia), processing method (Civer *vs.* Weasel) and variety of beans (Robusta (*Coffea canephora)* *vs*. Arabica (*Coffea arabica*)) by using both E-tongue and human sensory analysis. Therefore, three small studies were conducted to answer the above objectives by investigating in Experiment 1) different feeding conditions, Experiment 2) Thai civet coffee from the different geographical area with different feeding conditions, Experiment 3) civet coffee from different countries, processing method and variety of beans. MDS analysis was then applied to create the disparity and the distance matrices, while the E-tongue results were analyzed by PCA. The GPA technique was then applied to obtain the relationship between E-tongue measurements and consumer's perception of overall differences between the coffee samples. The methodology of this study is summarized in Fig. 1.

Table 1
Coffee bean samples used in the study.

Sample	Origin	Coffee type	Processing method	Feeding condition	Note
C-T-A-Cg	Doitung, Chiang Rai, Thailand	Arabica	Civet	Caged	
C-T-A-Fr-Ch	Doichang, Chiang Rai, Thailand	Arabica	Civet	Free-range	
C-I-A-Cg-Com	Indonesia	Arabica	Civet	Caged	Commercial grade
C-I-A-Cg-Pure	Indonesia	Arabica	Civet	Caged	High purity
C-T-A-Fr-Tg	Doitung, Chiang Rai, Thailand	Arabica	Civet	Free-range	
C-T-R-Fr	Loei, Thailand	Robusta	Civet	Free-range	
W-V-A	Vietnam	Arabica	Weasel		
N-T-A	Doitung, Chiang Rai, Thailand	Arabica	Normal		Premium grade

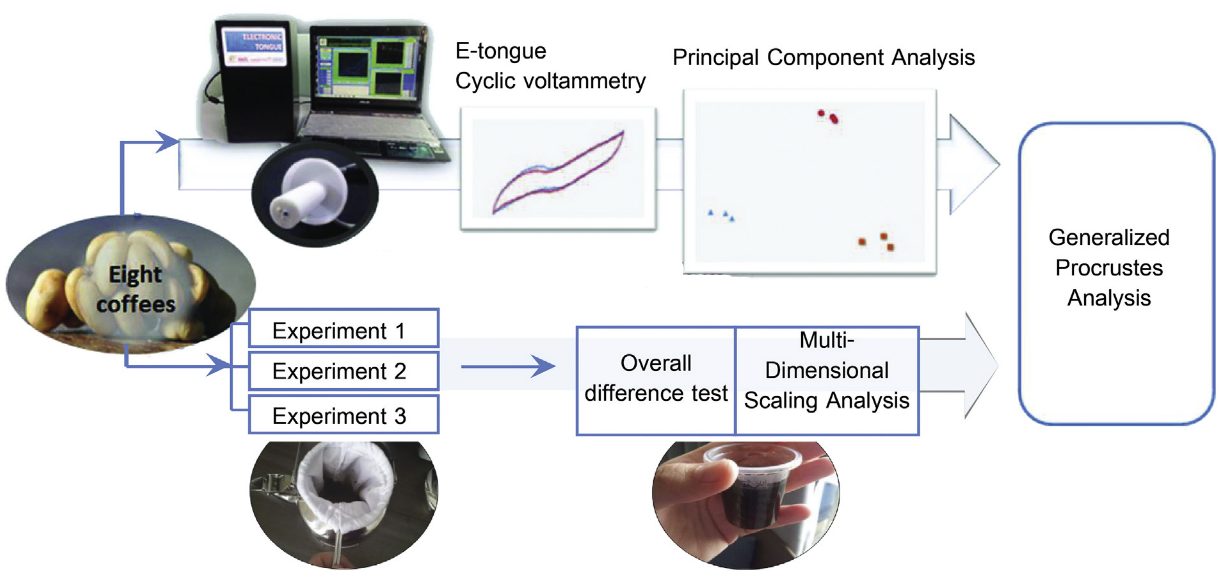

Fig. 1. Outline of methodology for obtaining relationship between E-tongue and sensory tests by overall difference method.

2. Materials and methods

2.1. Coffee materials

The list of coffee materials is shown in Table 1. Normally wet-processed Thai Arabica coffee beans (N-T-A, from Mae Sai District, Chiang Rai) were used as a reference (Slow Coffee™, Chiang Rai). All the beans were dried to 8–11% (w.b.) and were professionally roasted to medium-roast level according to each estate's roasting technique.

2.2. Coffee sample preparation

All coffee bean samples were prepared on the day of the testing by grinding using a coffee grinder (Braun, USA) set at the grinding level of 6. The ground coffee bean samples were packed separately in laminated re-sealable pouch. The steeping method was used to brew the coffee bean samples. Eight grams of a coffee bean sample was steeped through a cotton strainer using 100 ml hot water (98–100° C) for 4 min (Lyman et al., 2003). Then, the ground coffee beans were discarded. The coffee samples were served in a 60 ml plastic cup (EPP, Thailand) with 20 ml of freshly brewed coffee in the cup at 70 ± 2° C. Samples were presented in pair according to a presentation design, with a holding time in the cup no more than 2 min to reach the final temperature of the sample of approximately 40 ± 2° C.

2.3. E-tongue evaluation

E-tongue was constructed in-house and equipped with a low-noise data acquisition circuit with the NI-6009 interface controlled by the Labview software package. The electrodes, which were embedded in a Teflon rod, comprised of gold wire (1 mm diameter), graphite rod (Staedtler™ 2H, 2 mm diameter) as the working electrodes, and platinum (Pt) wire (0.3 mm diameter of 0.5 cm in length) as the quasi-reference electrode. This Pt reference electrode was demonstrated for electrochemical applications (Kasem and Jones, 2008). The use of the Pt quasi-reference electrode for electronic tongue applications was demonstrated (Chodjarusawad et al., 2016). The performance of this quasi-reference electrode in comparison to the standard Ag/AgCl reference has also been investigated and will be published elsewhere. This robust design allowed the coffee samples to be measured by E-tongue at the serving temperature, alongside the panel test. For each sample of the eight coffee beans, 30 ml of brewed coffee was collected, stored at 70 ± 2° C and allowed to cool down to approximately 40–45° C before each measurement. The electrodes were submerged by approximately 1 cm under the surface of the coffee sample. The electrodes were manually cleaned with a detergent solution, rinsed and calibrated with de-ionized water before every measurement.

2.4. Overall difference testing by consumers

For each panel test experiment, 12–14 consumers (different consumers for each experiment) were asked to rate the overall difference of six pairs of coffee samples on a four-point overall-difference scale using two-step questioning procedure: 1st) asking the consumers to declare their perception of differences (Yes/No) and 2nd) asking them to declare the level of sureness of their differences decision (Sure/Not sure). This resulted in four categories of overall differences: 1 = Not different-sure, 2 = Not-different-not sure, 3 = Different-not sure and 4 = Different-sure.

For the sensory test, consumers who were all coffee drinkers were provided with consent forms consistent with human subjects' approval and a ballot. All responses were collected using paper ballots. The order of presentation was randomized with the Williams design to account for presentation order effects (Schlich, 1993). Panelists were prompted to taste the sample by sipping the sample presented on the left first followed by sample on the right. Sipping water between the two samples was mandatory to rinse their palettes. In addition, to prevent carry-over effects from one pair test to another, panelists were obliged to follow a rinse procedure of sipping, then, spitting the water out.

2.5. Statistical analysis

2.5.1. E-tongue

Cyclic voltammertic (CV) characteristic data of food samples on E-tongue were preprocessed by the first derivative of signals for row preprocessing (Oliveri et al., 2010). CV measurements were conducted with the scan range of −1.5–1.5 V, the rate of 0.2 V/s with three scan loops. The CV current data for each loop were preprocessed by extracting averaged current values at a 0.25 V interval. All E-tongue data were arranged in a matrix and preprocessed by column centering technique as shown in Oliveri et al. (2010). The data acquisition and the PCA of this instrument were achieved by the LabVIEW software package. The mean value and the standard deviation of each parameter were determined for the data set. A zero-centered co-variance matrix was constructed as an input for the PCA calculations.

2.5.2. Overall difference test

The overall difference test was divided into three groups, with four coffee samples in each group, as shown in Table 2. Each experiment was designed to address a certain set of hypotheses by making a comparison between a specific set of coffee samples. For each experiment, a proximity matrix was created directly from the proportion of consumers who rated that "the pair of coffee samples was surely different". The estimate of difference-sureness rating means for each coffee samples were done using ANalysis Of VAriance (ANOVA). Then the matrices were subjected to separate MDS analyses. Scaling by MAjorizing a COnvex Function (SMACOF), a matrix MDS algorithm with Absolute MDS option, was used with the criterion of Kruskal's Stress1 less than 0.1. All statistical analyses were performed at 95% confidence level using XLStat v.2014.1.10 (Addinsoft, Paris, France).

2.5.3. Finding relationship between E-tongue and MDS solutions using GPA

GPA was performed on the PCA loading scores (3 dimensions extracted) of all eight samples from E-tongue evaluation and three sets of MDS-coordinates (using 3-dimension solutions) of the four samples from each experiment. There were a total of four data matrices: E-tongue, Experiment 1, Experiment 2 and Experiment 3 in this analysis. Gower procedure with an option of incomplete data set was used to study the correlation between perceptual construct similarities and differences between E-tongue and consumers' overall difference spaces (represented by MDS spaces from 3 studies). GPA dimensions that were highly correlated were further investigated for attributes that may have caused the significant correlations (PCA factor loading). All statistical analyses were performed at 95% confidence level using XLStat v.2014.1.10 (Addinsoft, Paris, France).

3. Results and discussion

3.1. E-tongue evaluation

A clear separation between Robusta civet coffee (C-T-R-Fr) and Arabica coffees (…-…-A-…) is shown in Fig. 2. Additionally, the coffee from N-T-A is well separated from the others. The first and the second principal components (PCs), E-tongue 1 and E-tongue 2 respectively, E-tongue 1 (50.5%) and E-tongue 2 (21.4%), drives this separation. E-tongue 1 separates C-T-R-Fr from Arabica civet/weasel coffees and E-tongue 2 separates civet coffees from N-T-A with additional separation between Robusta and Arabica coffees in the bottom region (Fig. 2a). Meanwhile, the third PC (E-tongue 3), (E-tongue 3 (8.6%), Fig. 2b) appears to a certain extent to separate coffee origins as Indonesian civet coffees (C-I-A-Cg) were in the negative side, Thai civet (C-T-…-…) and N-T-A were in the middle range (0–0.6) and Vietnamese weasel coffee (W-V-A) was well-separated to the top right (Fig. 2b). This separation is less definite in the case of high purity Indonesian civet coffee (C-I-A-Cg-Pure) and Thai free-range civet coffee from Doitung (C-T-A-Fr-Tg), particularly if the approximate data boundaries from three repetitions displayed for each data point are taken into consideration. The distinction in the origin of coffees by E-tongue 3 most likely occurs as a result of the processing method (e.g. different types of animals). The separation of the data as a result of different processing methods is apparent in both E-tongue 2 and E-tongue 3 (Fig. 2) when only coffees from the same area of Doitung, Chiang Rai, are considered (i.e. N-T-A, C-T-A-Cg, C-T-A-Fr-Tg). Not only the civet and

Table 2
Detail of Overall difference test in each experiment.

Experiment	Comparison	Coffee samples
1	Civet coffees at different feeding conditions	C-T-A-Cg C-I-A-Cg-Pure C-T-A-Fr-Tg N-T-A (reference)
2	Civet coffees from same the nearby area within Thailand with different feeding conditions	C-T-A-Cg C-T-A-Fr-Tg C-T-A-Fr-Ch N-T-A (reference)
3	Civet coffees from different countries, processing method and bean types	W-V-A C-T-A-Cg C-T-R-Fr C-I-A-Cg-Com

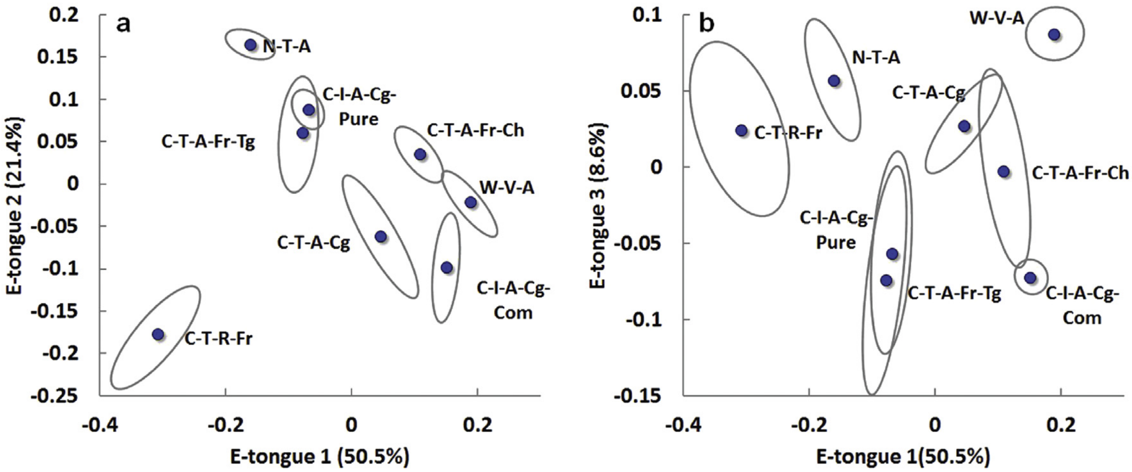

Fig. 2. PCA score plots of E-tongue measurements for all coffee samples: a) PC1 and PC2, b) PC1 and PC3. Each point represents the centroid with a data boundary as shown.

the non-civet coffees are separated, but also the different feeding conditions may be distinguished. On the whole, E-tongue measurements are able to distinguish the civet and the non-civet coffees, the type of coffee beans, the processing methods and the coffee origins.

3.2. Overall difference tests

3.2.1. Experiment 1: comparing civet coffee from different feeding conditions

In this experiment, civet coffees with different feeding conditions: C-T-A-Cg, C-I-A-Cg-Pure; and C-T-A-Fr-Tg were studied (with an addition of N-T-A as a reference). Table 3 shows the percent of the consumers who declared that coffee-pairs were different with “sure” conviction (Yes-sure) and averaged overall-difference rating for corresponding pairs. The differences between the coffee samples are more clearly illustrated in Fig. 3. C-T-A-Cg, C-T-A-Fr-Tg and N-T-A were significantly distinguishable by consumers (Yes-sure of 92.3%). Civet coffees with different feeding conditions were the second most significantly different (78.6%). C-I-A-Cg-Pure was not significantly different from the others, regardless of free-range and caged feeding conditions. The distinction between civet and non-civet coffees as perceived by the consumers also disappears (Yes-sure of 50%) in the case of the Thai non-civet and the Indonesian civet coffees.

Comparing the sizes of the percent “Yes-sure” (Table 3) to the distances between the coffee data points in E-tongue space (Fig. 2a) yields a very agreeable result. The closer the coffees in the PCA space, the lower the percentages of “Yes-sure”. This indicates that consumer's overall-difference perception was captured with E-tongue 1 and E-tongue 2, with some influences of E-tongue 3.

Fig. 4 shows consumer's overall-difference perceptual space unfolded by the MDS analysis. To capture the differences among the coffee samples, three dimensions were required. Comparing Fig. 4a to Fig. 2a shows some similarity between the two spaces, especially the closeness of C-I-A-Cg-Pure and C-T-A-Fr-Tg and the large separation of C-T-A-Cg and N-T-A. Interestingly, Fig. 4b (EXP1-1 and EXP1-3) exhibits quite a similar arrangement of C-T-A-Cg, N-T-A and C-T-A-Fr-Tg coffees to Fig. 1b (E-tongue 1 & 3). These results indicate that E-tongue space may have some correlation with consumers' overall-difference perceptual space.

3.2.2. Experiment 2: comparing Thai civet coffees from the same area (Doitung, Chiang Rai, Thailand) and nearby area (Doichang, Chiang Rai, Thailand) with different feeding conditions

In this experiment, C-T-A-Cg and C-T-A-Fr-Tg were evaluated against one another. N-T-A as a reference was an Arabica coffee from the same Doitung area as C-T-A-Cg and C-T-A-Fr-Tg. The

Table 3
Percent of consumers who declare “Yes, sure” and the ANOVA-averaged overall-difference ratings (1–4 points) for all coffee pairs from the three experiments.

Exp.	Pair		Difference -sure (%)	Overall-difference rating
1	C-T-A-Cg	N-T-A	92.3	3.8
	C-T-A-Fr-Tg	C-T-A-Cg	78.6	3.6
	C-T-A-Fr-Tg	N-T-A	64.3	3.4
	C-I-A-Cg-Pure	C-T-A-Cg	64.3	3.2
	C-I-A-Cg-Pure	C-T-A-Fr-Tg	57.1	3.4
	C-I-A-Cg-Pure	N-T-A	50.0	3.1
2	C-T-A-Cg	N-T-A	92.3	4.0
	C-T-A-Fr-Tg	N-T-A	85.7	3.8
	C-T-A-Fr-Tg	C-T-A-Cg	78.6	3.5
	C-T-A-Fr-Ch	C-T-A-Cg	71.4	3.5
	C-T-A-Fr-Ch	N-T-A	57.1	3.2
	C-T-A-Fr-Ch	C-T-A-Fr-Tg	42.9	2.8
3	W-V-A	C-T-A-Cg	92.3	4.0
	W-V-A	C-I-A-Cg-Com	76.9	3.7
	W-V-A	C-T-R-Fr	76.9	3.8
	C-T-A-Cg	C-I-A-Cg-Com	69.2	3.4
	C-T-R-Fr	C-I-A-Cg-Com	69.2	3.4
	C-T-R-Fr	C-T-A-Cg	53.8	3.3

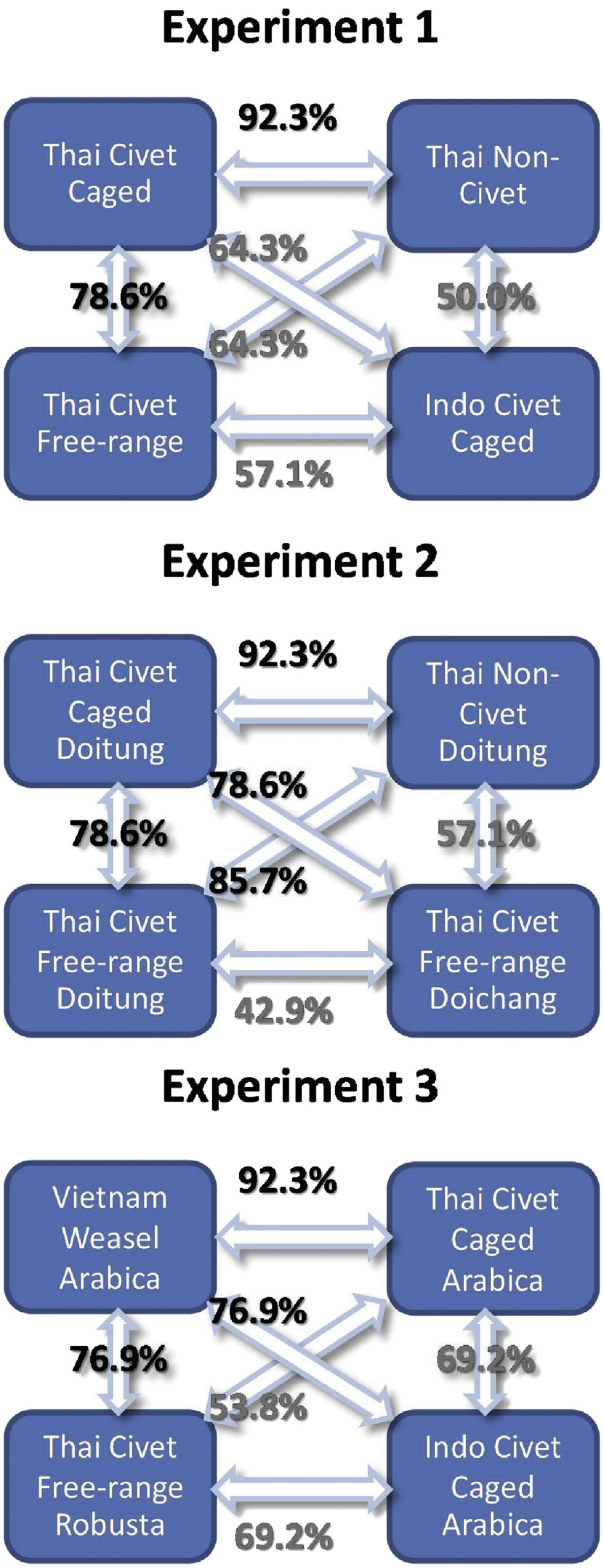

Fig. 3. Percent of consumers who declare "Yes, sure" for all coffee pairs from all three experiments.

results are tabulated in Table 3. The percentages of "Yes-sure" amongst these coffees are better depicted in Fig. 3. The civet and the normal-process coffees from the same Doitung area show the most significant difference. Besides the differences between processing conditions (normal wet *vs.* civet processes), different feeding conditions within the same area (Doitung) was the third most significant difference.

An interesting finding may be found when C-T-A-Fr-Ch coffee from the nearby Doichang area is compared to the three Doitung samples (Fig. 3). The same finding may be found in Experiment 1, in which the differences between feeding conditions are smaller when civet coffee samples from different areas are compared (Indonesia *vs*. Thailand in Experiment 1 and Doichang *vs*. Doitung in Experiment 2). In Experiment 2, the difference (78.6%) of the coffees from different area with different feeding conditions is still significantly larger than that (57.1%) those of the coffees from different areas and different processing conditions. Based on this trend, the civet coffees from different area with the same feeding conditions (free-range) were not significantly different from each other (42.9%).

Interestingly, the impact of different areas appears to reduce the impact of feeding and processing conditions. The distances between coffee samples in the PCA space in Fig. 2 are roughly in agreement with the "Yes-sure" percentages from the consumers (Table 3). The MDS analysis (Fig. 5) also exhibits a similar pattern of the MDS space to the E-tongue space (Fig. 2), with the C-T-A-Fr-Ch well-separated from the other three. In addition, the Exp2-3 axis differentiates the different feeding and processing (civet *vs*. normal wet processes) conditions.

3.2.3. Experiment 3: comparing civet coffees from different countries, processing method (civet vs. weasel) and bean types

One of the objectives of this experiment was to compare civet coffees from different countries mainly from Indonesia, Thailand and Vietnam. However, Vietnamese coffee samples commercially available as "civet coffee" were, in fact, made from weasels (W). The results are again listed in Table 3 and depicted in Fig. 3. This "weasel" coffee exhibits the largest differences from the other civet coffees from Thailand and the commercial grade caged civet coffee from Indonesia, regardless of the type of coffee beans used (Robusta or Arabica). The MDS analysis requires three-dimension solutions to explain these differences (possibly three different sensory attributes) (Fig. 6). In addition, the civet coffees from Thailand and Indonesia are also rather different (Fig. 3), but not as much as those differences when compared to the Vietnamese weasel coffee. Comparing coffees of different types and different feeding conditions from the same country (Thailand) yields a non-significantly different result. The distribution of the data points in the MDS space for Experiment 3 (Fig. 6) again resembles that in the E-tongue space (Fig. 2), with a clear separation of the weasel coffee.

3.3. Relationship between E-tongue measurement and consumers' perception of overall differences of civet coffees

Fig. 7 shows the locations of all coffees samples from the three experiments in a combined space from E-tongue and the MDS analysis from the three experiments. The space is analogous to the PCA score plot. With three dimensions, all coffees are distinguishable from each other. The GPA spaces in Fig. 7a and b clearly resemble the E-tongue spaces in Fig. 2a and b, respectively, since the GPA results are essentially the E-tongue space refined by the MDS results from the overall difference tests. GPA 1 (48.3% variance) seems to differentiate coffee bean types. GPA1 and GPA 2 (33.2%) together (Fig. 7a) could differentiate processing and feeding conditions.

The correlations between E-tongue principal component axes (E-tongue 1, 2 & 3) and the MDS dimensions from the three experiments (Exp1-1, 2&3; Exp2-1, 2&3 and Exp3-1, 2&3) are

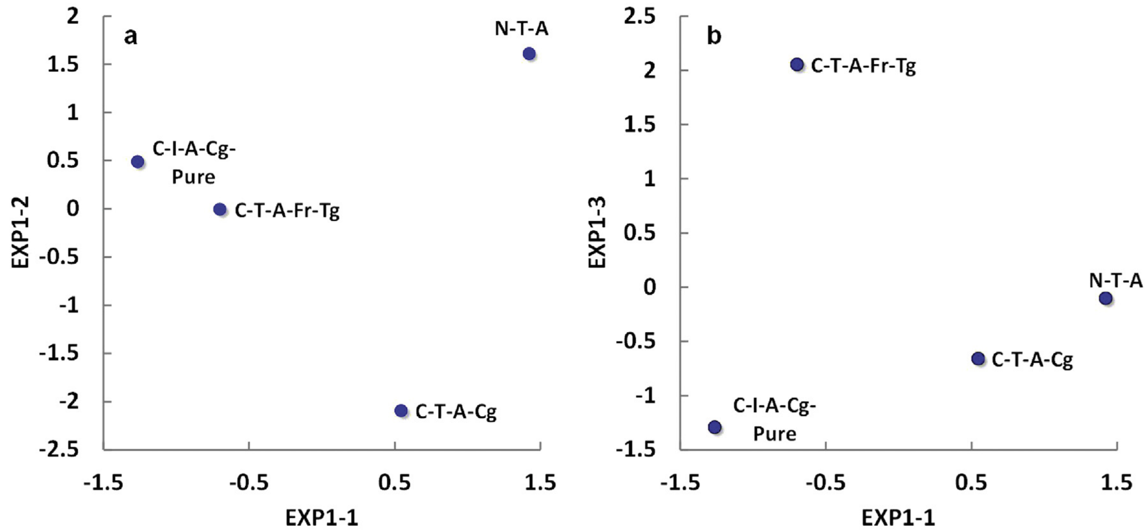

Fig. 4. MDS Overall difference perceptual space from Experiment 1, Kruskal's stress (1) of 3-dimensional solution was 0.00003. (a) Dimensions 1 and 2, (b) Dimensions 1 and 3.

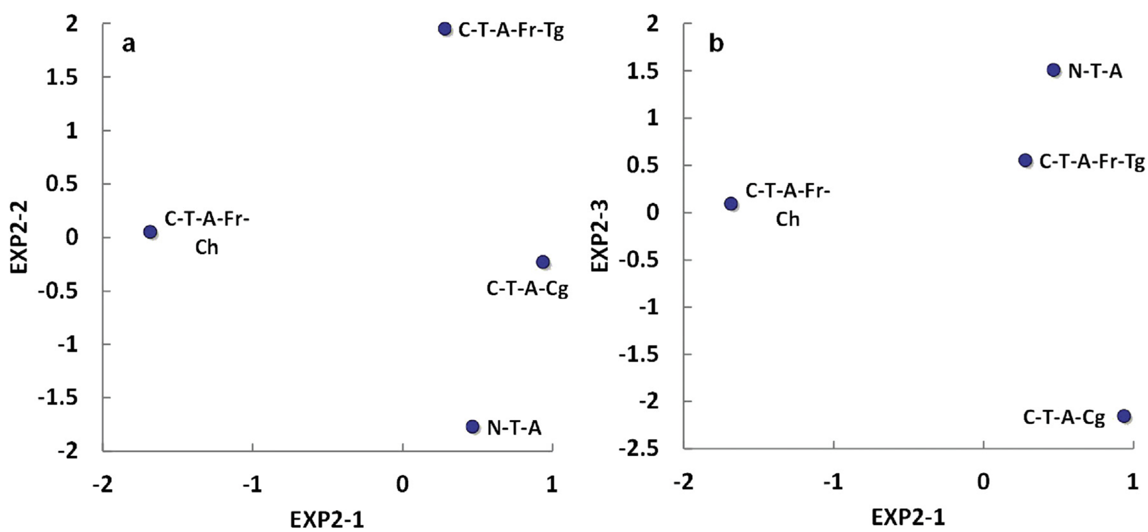

Fig. 5. MDS Overall difference perceptual space from Experiment 2, Kruskal's stress (1) of 3-dimensional solution was 0.00003. (a) Dimensions 1 and 2, (b) Dimensions 1 and 3.

obtained from GPA, as shown in Table 4. Dimensions with strong correlations (with the magnitude above 0.7) to the GPA axes GPA are highlighted in bold. This allows matching of multi-dimensional structures/spaces, in analogous to the PCA loading plot. In this study, matching the E-tongue space with the three perceptual spaces from the three experiments provides the meaning to E-tongue measurements based on human perception of overall differences between coffees.

E-tongue 1, 2, and 3 are well correlated to the three GPA dimensions, GPA1, GPA2, and GPA3, respectively. This confirms the E-tongue space as the main contribution to the GPA space. E-tongue 1 shows strong negative correlation with Exp1-2 and Exp3-2, whereas E-tongue 2 exhibits strong positive correlation with Exp1-2, Exp2-3 and Exp3-1. The large negative values also signify that the data are highly correlated but in the opposite sense, which only depends on the order of the data in the matrices. E-tongue 3 shows strong positive correlation with Exp1-1, Exp3-1 and strong negative correlation with Exp2-2.

The meanings of each E-tongue axes are best extracted using the summary of overall different characteristics from the MDS analysis of the three experiments in Table 5. The characteristics listed for each dimension start from the most significant. The characteristics that are well distinguished by the overall difference tests include processing methods, feeding conditions, animals used in the process, countries of origin. The others that are less distinct include coffee types and local areas. When these characteristics are related to Table 4, the physical meanings may be assigned to the E-tongue space. E-tongue 1 (correlated to Exp1-2 and Exp3-2) is able to distinguish mainly the processing methods. The countries of origins are also possibly separated by E-tongue 1 but more Indonesian and Vietnamese coffees are needed for a more conclusive study. E-tongue 2 (correlated to Exp1-2, Exp2-3 and Exp3-1) is able to separate the feeding and the processing conditions (free-range, caged, normal wet, civet). E-tongue 3 (correlated to Exp1-1, Exp2-2 and Exp3-1) shows a similar characteristic to E-tongue 2, but with the addition ability to distinguish civet and weasel coffees. The remaining two characteristics that are not correlated to the E-tongue space are the coffees from nearby areas and the type of coffees, even though the two coffee samples responsible for these characteristics (C-T-A-Fr-Ch and C-T-R-Fr) are well separated from

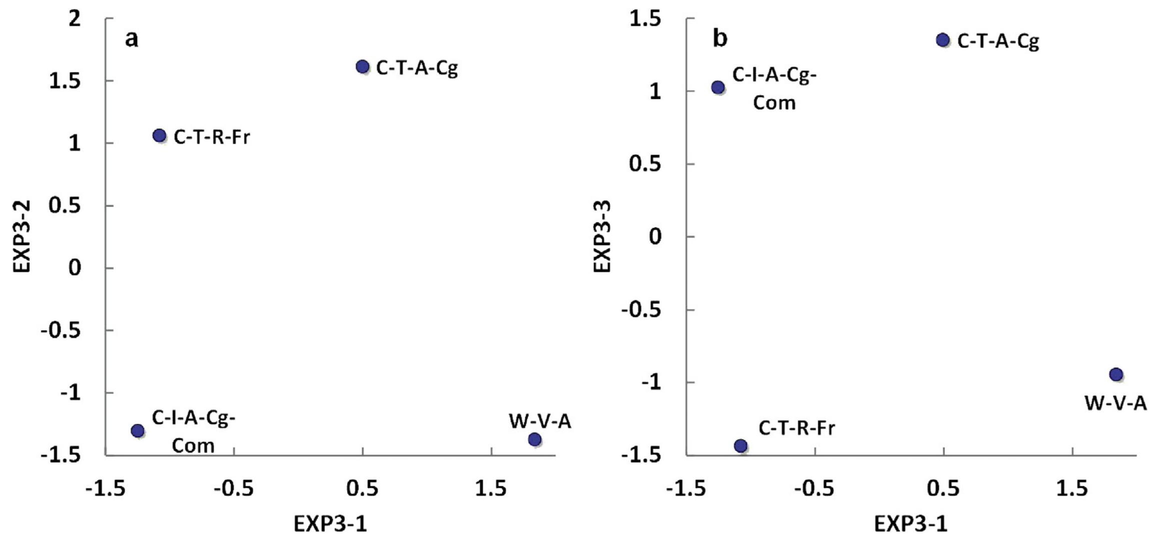

Fig. 6. MDS Overall difference perceptual space from Experiment 3, Kruskal's stress (1) of 3-dimensional solution was 0.00002. (a) Dimensions 1 and 2, (b) Dimensions 1 and 3.

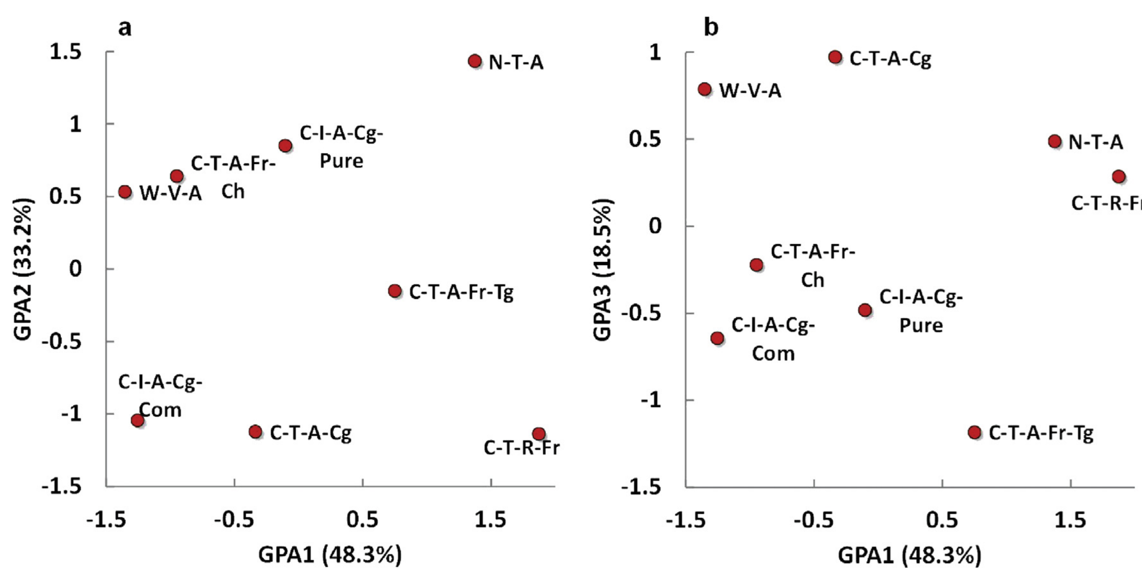

Fig. 7. GPA space of all coffee samples representing combined space from E-tongue and MDS-spaces from the three experiments (a) Dimensions 1 and 2, (b) Dimensions 1 and 3.

Table 4
Correlation between E-tongue PC-scores and MDS dimensions from the three experiments. The numbers indicate the degree of correlation to GPA dimensions. Bold font indicates >0.7 correlation to GPA dimensions.

Original dimension	GPA1 (48.3%)	GPA2 (33.2%)	GPA3 (18.5%)
E-tongue1	**−0.98**	0.03	0.03
E-tongue2	0.08	**0.88**	−0.18
E-tongue3	0.07	0.25	**0.90**
Exp1-1	0.48	0.11	**0.76**
Exp1-2	**0.78**	**0.97**	−0.33
Exp1-3	0.51	−0.17	−0.59
Exp2-1	0.59	−0.40	0.36
Exp2-2	−0.20	−0.51	**−0.79**
Exp2-3	0.64	**0.89**	−0.47
Exp3-1	−0.47	**0.83**	**0.77**
Exp3-2	**0.70**	−0.62	0.48
Exp3-3	−0.50	−0.43	−0.16

the rest on the E-tongue space (Fig. 2). The reason is that these two characteristics are not conclusively distinguished by the consumers with low percentages of “Yes-sure” in the overall difference tests.

4. Conclusion

A newly developed cyclic voltammertic E-tongue successfully differentiates coffees brewed from different processing conditions (Civet cat *vs.* Weasel *vs.* normal wet-process), feeding conditions, coffee beans (Robusta *vs.* Arabica), harvesting countries (Thailand *vs.* Indonesia *vs.* Vietnam) and harvesting area within a country (Doitung *vs.* Doichang). These differences were validated by consumers especially the differences due to the processes and feeding conditions as well as the coffee bean types (Robusta and Arabica) from a normal wet-process condition (positive control). The nearby growing regions (Doitung and Doichang) are found to influence the consumer perception on distinguishing different processing and feed conditions. Correlation between the cyclic voltammertic E-tongue measurements and consumers' overall perceived differences were established and quantified. The results endorse a new

Table 5
Qualitative summary of overall different characteristics extracted from the MDS analysis of the three experiments. The characteristics in each dimension are listed from the most significant first.

Original dimension	MDS overall different characteristics
Exp1-1	Processing (normal wet *vs*. civet)
	Countries (Thailand *vs*. Indonesia)
Exp1-2	Processing (normal wet *vs*. civet)
Exp1-3	Feeding (free-range *vs*. caged)
	Processing (normal wet *vs*. civet)
	Countries (Thailand *vs*. Indonesia)
Exp2-1	Nearby area (Doitung *vs*. Doichang)
Exp2-2	Processing (normal wet *vs*. civet)
	Feeding (free-range *vs*. caged)
Exp2-3	Feeding (free-range *vs*. caged)
	Processing (normal wet *vs*. civet)
Exp3-1	Processing (civet *vs*. weasel)
	Countries (Thailand, Indonesia, Vietnam)
Exp3-2	Countries
	(Thailand *vs*. Indonesia & Vietnam)
	Processing (civet *vs*. weasel)
Exp3-3	Coffee type (Robusta *vs*. Arabica)

application of the use of this cyclic voltammertic E-tongue as a promising tool for quality control, product development and agricultural management. Further study to identify sensory attributes that are responsible for these perceptual differences among coffees will enhance the descriptive ability of E-tongue beyond just discrimination of coffees.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jfoodeng.2016.02.011.

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