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Triadic discrimination testing: refinement of Thurstonian and Sequential Sensitivity Analysis approaches

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Abstract. The effect of cognitive search strategies and variations in the oral environment on discrimination test performance were investigated. Subjects were required to discriminate between low concentration NaCl solutions and water using the 3-AFC and triangle test protocols. As predicted by Thurstonian modeling, subjects obtained a higher proportion of correct tests for the 3-AFC protocol than for the triangle protocol. The d' values obtained from both protocols corresponded. As predicted by the Sequential Sensitivity Analysis Model, which is largely based on changes in the oral environment, subjects obtained a higher proportion of correct tests for triads containing one NaCl stimulus than for triads containing one water stimulus. Measurement of physical signal strengths of the stimuli, by analysing the Na cation concentration change in the oral environment on tasting, indicated that the classical Thurstone-Ura two-distribution model was insufficient. The strong carry-over effects in the chemical senses require a model based on more than two distributions. It was also noted that subjects did not always use the search strategy required for a given test protocol. The artifactual effects of strategy change during an experiment are discussed.

Introduction

Forced-choice discrimination testing protocols for foods and stimuli for the chemical senses vary in their sensitivity in that judges may be better at detecting differences using one test protocol than they would be when using another (Helm and Trolle, 1946; Dawson and Dochterman, 1951; Byer and Abrams, 1953; Hopkins, 1954; Hopkins and Gridgeman, 1955; Gridgeman, 1955, 1956; Filipello, 1956; Mitchell, 1956; Hogue and Briant, 1957; Dawson *et al.*, 1963; Grim and Goldblith, 1965; Wasserman and Talley, 1969; Spencer, 1979; Pokorný *et al.*, 1981; O'Mahony *et al.*, 1986; Buchanan *et al.*, 1987; Francois and Sauvageot, 1988; Thieme and O'Mahony, 1990; MacRae and Geelhoed, 1992; Stillman, 1993). Thurstonian ideas (Thurstone, 1927a, b) were used to develop models for the 2-AFC, triangular and duo-trio methods by Ura (1960). More broadly, others have contributed univariate modeling (Mosteller, 1951a, b, c; Bradley, 1963; Vessereau, 1965; Frijters, 1979a, b, 1980, 1981,a, b) and multivariate modeling (Ennis and Mullen, 1985, 1986a, b, 1992a, b; Kapenga *et al.*, 1987; Mullen and Ennis, 1987, 1991; Mullen *et al.*, 1988; Ennis *et al.*, 1988a, b; Ennis, 1988a, b, 1990, 1992). Such models have been used to produce tables of d' (sometimes expressed as δ) corresponding to the proportion of correct responses for various forced-choice procedures (Ura, 1960; Elliott, 1964; Hacker and Ratcliff, 1979; Frijters *et al.*, 1980; Frijters, 1982; Ennis and Mullen, 1986b; Ennis, 1990).

Frijters (1979a, 1981a) used the Thurstonian modeling approach to explain a result obtained by Byer and Abrams (1953) which subsequently became known as the paradox of discriminatory nondiscriminators. The paradox refers to an apparent discrepancy in performance between the triangle (Peryam and Swartz, 1950; Peryam, 1958) and the 3-AFC (Green and Swets, 1966) discrimination methods. These are both triadic forced-choice procedures, yet they vary in the instructions given to the subject and in the particular permutations of stimuli presented in the triad.

Consider two confusable stimuli, S and N, of which S is slightly stronger than N. For the 3-AFC method, triads consisting of one S and two Ns (SNN, NSN, NNS) are presented to the subject with the instructions to identify the S (stronger) stimulus. The nature of the difference is specified (e.g. 'In the following triad, there will be one sweeter stimulus and two less sweet stimuli; identify the sweeter stimulus'). The complementary 3-AFC is also available (one N and two Ss), with suitable modification of instructions. For the triangular method, all six possible permutations (SNN, NSN, NNS and NSS, SNS, SSN) are presented to the subject who does not know whether S or N is the odd stimulus. The instructions are to find the odd stimulus.

The search procedure for the triangular method requires the judge to compare distances along the perceptual intensity continuum between the momentary intensities of the three stimuli. The 3-AFC requires the subject merely to identify the momentary intensity which is furthest towards the strong (or weak) end of the perceptual intensity continuum. The pioneering work of Frijters (1979a, 1982) noted how this difference in strategy brought about a higher proportion of correct 3-AFC than triangle tests for a given d' and also produced usable tables of d' for these two methods.

In modeling these two methods, the distributions of intensities for separate stimuli are assumed to be independent. This implies that the taste (or smell) of a stimulus is not affected by the taste (or smell) of the preceding stimulus. With suitable presentation procedures and interstimulus protocols (O'Mahony, 1979; Halpern, 1986), it is possible to fulfill this requirement, but, generally, there will be sequence effects. So strong are these sequence effects that an ordinal model of discrimination test sensitivity has been based upon them: Sequential Sensitivity Analysis (SSA). It has been applied to discrimination between food stimuli (O'Mahony and Goldstein, 1986), as well as discrimination between low concentration NaCl taste stimuli and water (O'Mahony and Odbert, 1985; O'Mahony and Goldstein, 1987; Vié and O'Mahony, 1989).

For NaCl and water taste stimuli, the model used R-index signal detection measures [O'Mahony, 1992; equivalent to P(A); Green and Swets, 1966] to determine that on average, the relative detectability of NaCl and water stimuli depended on whether the preceding stimulus was NaCl or water. Thus, NaCl tasted after water (W-S) was the most easily detected. Water tasted after NaCl (S-W) was the second most easily detected. Water tasted after water (W-W) was third, NaCl tasted after NaCl (S-S) was least easily detected. It should be noted that this order of detectability was the mean order over 62 subjects; there were many individual exceptions (Vié and O'Mahony, 1989). The order itself was determined by a complex interaction of adaptation, variability in physical signal strengths caused by mixing with saliva, stimulus learning and the relative detectability of supra- and subadapting stimuli (O'Mahony and Goldstein, 1987).

These relative detectabilities were utilized when examining the sequence of tasting in various discrimination protocols. Some protocols have sequences of tasting which involve a higher proportion of more detectable stimuli (W-S, S-W), while other protocols have a higher proportion of less detectable stimuli (W-W, S-S). In the former protocols, stimuli are on average more detectable and the subject tends to perform better on such discrimination tests.

For triadic tests, SSA predicts that subjects will, on average, discriminate better on triads with one NaCl and two water stimuli than on triads with two NaCl and one water stimulus. This is a simple consequence of the number of sequence pairs (W-S, S-W, W-W, S-S) that occur in each set of triadic sequences and it was confirmed experimentally (O'Mahony and Odbert, 1985; O'Mahony and Goldstein, 1987). However, Thurstonian modeling predicts the same result if the assumption is made that the distribution of perceived intensities for the NaCl stimulus has greater variance than the distribution of perceived intensities for the water stimulus.

This study tested hypotheses generated both by SSA and Thurstonian modeling approaches to the triangular and 3-AFC methods, for discrimination between the tastes of low concentration NaCl and water. Several hypotheses were tested:

(i) For a given subject and a given pair of stimuli, a higher proportion of 3-AFCs would be performed correctly than triangles. This allows confirmation of earlier results.

(ii) For a given subject and a given pair of stimuli, the *d'* obtained from the proportion of correctly performed 3-AFCs would correspond to the *d'* obtained from the proportion of correctly performed triangles. This tests whether the decision rules are correct in the modeling; if they are not, *d'* values will not correspond.

(iii) For 3-AFCs and triangles, a higher proportion of triads containing one NaCl and two water stimuli would be performed correctly than for triads containing one water and two NaCl stimuli. This tests a prediction from both SSA and Thurstonian modeling.

Because taste stimuli will mix with the fluids in the oral cavity before stimulating taste receptors, thus altering the physical signal strengths, it was decided that these physical signal strengths should be measured. The fluid present in the oral cavity before tasting a given stimulus will be a mixture of secreted saliva and residual stimulus left over from prior tasting (O'Mahony, 1979; O'Mahony and Goldstein, 1987). The concentration of NaCl in this fluid will depend on the ever changing concentration of NaCl in secreted saliva and the NaCl concentration of prior tasted stimuli. For example, if the previously tasted stimulus was water, the NaCl concentration in the oral fluid would be lower than if the priorly tasted stimulus was NaCl. This provides a major source of variance for the NaCl concentration in the mouth prior to tasting.

The current model of NaCl taste adaptation (McBurney and Pfaffmann, 1963; Bartoshuk *et al.*, 1964; Bartoshuk, 1968, 1974, 1978, 1980) hypothesizes that the taste of NaCl depends on prior adaptation. NaCl taste receptors are conceived as adapting to the NaCl content (strictly to the Na^+ content) of their surrounding medium. For moderate concentrations in the salivary range, the adaptation process results in the adapting solution being perceived as tasteless. This can be conceptualized as the taste system setting its taste zero to the adapting concentration (O'Mahony, 1979). For the low concentrations encountered in this study, it can be assumed that the taste receptors will be completely adapted (will have set their 'taste zero') to the NaCl concentration in the mouth prior to tasting the stimulus. On tasting the stimulus, the NaCl concentration in the mouth will change. This change will be registered by the taste receptors as a taste sensation. An NaCl stimulus will tend to increase the NaCl concentration in the mouth (supra-adapting taste); a water stimulus will tend to decrease the NaCl concentration in the mouth (subadapting taste). These changes in physical signal strengths (increase or decrease in NaCl concentrations) were monitored by simply collecting the expectorated stimuli during testing for analysis. Such monitoring of the variation in physical signal strengths give clues about the variations in perceived signal strengths.

Materials and methods

Subjects

The experimental goal was to study in detail the sensory discrimination of a single subject, SS (F, age 20 years). Three further subjects: KH (F, 50 years), FH (M, 22 years), RS (M, 27 years) were studied to confirm the findings for the first subject. Thus, the experimental approach was longitudinal rather than cross-sectional.

Subjects refrained from eating or drinking (except water) for at least 1 h prior to testing. All subjects were non-smokers.

Stimuli

Stimuli were NaCl solutions and purified water. The NaCl solutions were made from reagent grade NaCl (Mallinckrodt, Inc., Paris, KY) dissolved in Milli-Q purified water, which also furnished the water samples [deionized water fed into a Milli-Q system: ion exchange and activated charcoal (Millipore Corp., Bedford, MA)]. The purified water had a specific conductivity of $<10^{-6}$ mho/cm and a surface tension of ≥ 71 dynes/cm. Stimuli were dispensed in 10 ml volumes using Oxford Adjustable Dispensers (Lancer, St Louis, MO) and presented to the judges in 1 oz plastic portion cups (S. E. Rykoff & Co., Los Angeles, CA). The temperature of the stimuli over the whole study was kept in the range 19.2–26.0°C. However, the temperature difference between stimuli during any experimental session never exceeded 0.2°C.

Testing procedures

An experimental session consisted of four types of measurement. First, subjects performed 12 triangles and 12 3-AFCs, discriminating between low concentration NaCl and purified water. Stimuli were sipped and expectorated. Secondly, sequence effects were measured. These referred to the subject's ability to detect NaCl when the preceding stimulus had been water (W-S) or when it had been NaCl (S-S) and to detect water when the previous stimulus had been water (W-W) or NaCl (S-W). The procedure used was O'Mahony and Odbert's (1985) modification of the signal detection rating procedure (Green and Swets, 1966); these data were used as the basis for subsequent Sequential Sensitivity Analysis of subjects' performance. Again, stimuli were expectorated. Thirdly, physical signal strengths were measured for stimuli tasted in the four sequences mentioned above: W-S, S-W, W-W, S-S. The physical signal strength was the change in NaCl concentration (strictly Na^+) upon tasting the stimulus. This was determined by requiring the subject to expectorate immediately before tasting the stimulus and immediately after. Expectorates were analysed for Na^+ concentration by atomic absorption spectrophotometer. Fourthly, saliva samples were taken and analysed for Na^+ to monitor secreted salivary NaCl concentration changes throughout the experimental session.

Experimental session: Overview

During an experimental session, these four types of measurement were presented in an order that balanced the effects of learning and fatigue/adaptation. Thus, the triangle and 3-AFC testing was split into two portions, with sequence effects measured in between. Physical signal strength measurement, which required less of the subject's attention, was tested at the end of the session. Thus, the testing sequence during an experimental session had four portions as follows:

(i) six triangles and six 3-AFCs;
(ii) sequence effects measurement;
(iii) six triangles and six 3-AFCs;
(iv) physical signal strength measurement.

Before each portion and at the end of the session, saliva samples were collected to monitor salivary NaCl concentration.

In a given session, the six triangles were all presented before the six 3-AFCs (in both portions). In other sessions, this order was reversed. The conditions were alternated randomly over sessions. Furthermore, there are six possible sequences of presentation for the triangular and 3-AFC methods; each occurred twice during an experimental session in randomized order.

Before each psychophysical part of the experimental session (portions 1 – 3), a warm-up procedure (O'Mahony *et al.*, 1988) was used to ensure that the subject had identified the signal to be detected. This ensured 'plateau' performance to avoid stimulus learning during data collection. The warm-up procedure consisted of alternate tasting of water and NaCl stimuli until the judge felt confident enough to proceed. At first, the two stimuli appeared identical but on repeated tasting subjects reported that the differences began to appear. For each warm-up, a subject was required to taste each stimulus at least five times; further tastings were allowed as required up to a total of 15 – 20 of each stimulus. The tastings required in each warm-up decreased as the session proceeded.

A diagrammatic representation of a session is given in Fig. 1.

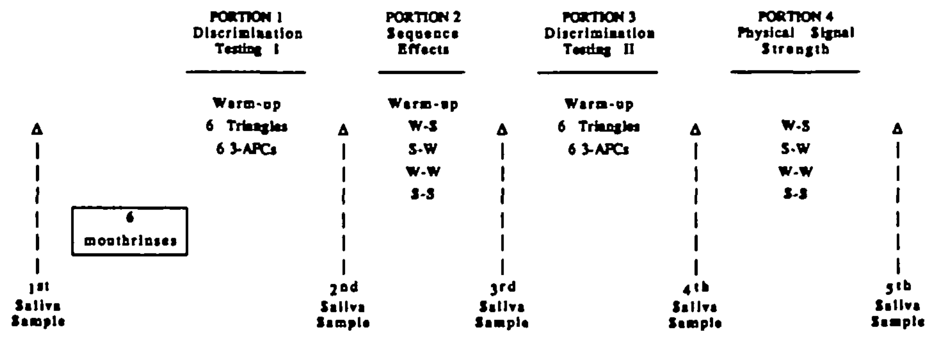

Fig. 1. Scheme of experimental session.

Psychophysical discrimination testing

The six possible tasting sequences for the triangular method were each presented twice during an experimental session, to give a total of 12 triangles. To vary the adaptation conditions and allow adequate physical stimulus variance, two water tastings were taken before each test in one set of six triangles and two NaCl tastings were taken before each test in the other set. These prior tastings were tasted and expectorated in exactly the same way as the stimuli within the triangle tests but the subjects were instructed to ignore their taste. The subjects believed them to be mere mouthrinses. The same procedure was used for the 3-AFCs.

At the very beginning of the experimental session, the experimenter first established a rapport with the subject and obtained relevant experimental details. The subject then expectorated to give the first saliva sample for monitoring NaCl concentration. This was collected in a plastic vial. The subject then rinsed 6 times with purified water to clean the mouth. The first portion of the experimental session (warm-up, six triangles, six 3-AFCs) was then performed (see Fig. 1). Because of the low stimulus concentrations used, no interstimulus rinses were taken during testing (Halpern, 1986; O'Mahony, 1979). Furthermore, it was intended that the slight adaptation changes should be allowed to elicit sequential tasting effects.

When necessary, instructions were given verbally; stimuli were presented to subjects on a clean, white tray (three triangles or 3-AFCs per tray). Subjects responded by placing the cup for the target sample (odd tasting stimuli: triangle method; salt or water stimuli: 3-AFC method) in another tray. For 3-AFCs, the trays were labelled to indicate whether salt or water was the target stimulus. The warm-up procedure and numerous practice sessions ensured that the subjects knew the tastes of purified water and low concentration NaCl.

After the triangles and 3-AFCs, the subject paused, but continued to move his mouth to mimic tasting and produce non-resting saliva. After approximately 15–30 s, his mouth filled with saliva and he expectorated. The subject repeated this procedure three more times to clear the mouth of stimulus residual. The saliva from the final expectoration was collected in a plastic vial to become the second saliva sample (see Fig. 1), to allow monitoring of the secreted salivary NaCl concentration during the experimental session. The subject then proceeded to the second portion of the experiment: measuring sequence effects.

Upon completion of the second portion, the subject gave a further saliva sample in the manner described above (third saliva sample, see Fig. 1). He then proceeded with a warm-up, six triangles and six 3-AFCs to complete the third portion of the experimental session. After this portion, a further saliva sample was collected (fourth saliva sample, see Fig. 1).

Measurement of sequence effects

The four possible sequences of tasting (W-S, S-W, W-W, S-S) were presented to the subject, either with a prior water tasting or a prior NaCl tasting to give a range of adaptation conditions. Accordingly, there were eight possible tasting sequences:

W W-S
W S-W
W W-W
W S-S
S W-S
S S-W
S W-W
S S-S

Each sequence was presented to the subject who tasted the first two stimuli in the sequence, ignoring their taste and then, on tasting the third stimulus, reported whether it was salt or water. The subject was informed that the first two stimuli were simply rinses whose taste should be ignored. To counter response bias, the subject also reported whether he was sure or unsure of his judgement. Therefore, the response categories available to the subject were: 'salt sure', 'salt unsure', 'water unsure', 'water sure'. From these data, R-index measures (O'Mahony, 1992), indicating the relative signal strengths of the stimuli in the sequences, could be computed (O'Mahony and Odbert, 1985). The R-index is the estimated probability of detecting a signal when presented in a 2-AFC with noise; it is equivalent in this particular case to Green and Swets' (1966) indices: P(C) and P(A).

Over five sessions, a total of 40 (5 × 8) sequences were tasted. These were presented in randomized order over each set of five sessions. This order was chosen to prevent outguessing by the subject. Instructions and subject's responses were given verbally; stimuli were presented as in portion 1.

In the experimental session, the sequence effects portion began immediately after the salivary collection at the end of the first discrimination testing portion (portion 2, see Fig. 1). No interstimulus rinses were taken during testing. At the end of this portion of the experiment, a saliva sample was collected in the usual way and subjects proceeded to the second set of discrimination tests (portion 3, see Fig. 1).

Physical signal strength measurement

After a saliva sample was taken at the end of the second set of discrimination tests (portion 3, see Fig. 1), physical signal strengths were measured. Subjects tasted stimuli in each of the eight possible sequences used for portion 2. However, instead of reporting the taste of the third stimulus in each sequence, the physical signal strength was measured. This was attained by collecting and analysing the expectorates of the second and third stimuli and noting the concentration change upon tasting the third stimulus. This change could be an increase in NaCl concentration (e.g. sequence pair W-S) or a decrease (e.g. sequence pair S-W).

Instead of tasting each of the eight sequences separately, they were combined to a single long sequence of tasting, such that all eight sequences occurred over segments of the long sequence. For example, the sequences W W-W and W W-S could be combined as a single sequence: W W W S. To combine all eight sequences, two orders of tasting were devised and chosen randomly: W-W-W-S-S-S-W-S-W-W and S-S-S-W-W-W-S-W-S-S. To calculate the required signal strengths, expectorates were collected for all stimuli except the first in each sequence.

At the end of this portion of the experiment, a final salivary sample was collected as before (fifth saliva sample, see Fig. 1).

Atomic absorption spectrophotometry

The expectorates from the fourth portion of the experimental session and the five saliva samples used to monitor salivary NaCl content throughout the session were analysed for NaCl content (strictly Na^+) using a Perkin-Elmer Atomic Absorption Spectrophotometer, Model 5000 (Perkin-Elmer Corp., Norwalk, Conn.). The calibration standards used were 1, 3 and 9 ppm Na^+ (0.043, 0.130 and 0.391 mM NaCl, respectively).

Saliva samples were collected from the subjects by expectorating into plastic vials (1 oz screw-top vial, Nalge Co., Nalgene Brand Products, Rochester, NY). They were then diluted for analysis by the spectrophotometer; their concentrations were required to fall between the first two standard concentrations (0.043–0.130 mM NaCl). Dilutions were performed by micropipetting 0.05–0.1 ml aliquots of saliva (Oxford Sampler Micropipetting, Oxford Labware, Division of Sherwood Medical, St Louis, MO) into 5 or 10 ml volumetric flasks to be diluted by the addition of purified water. The exact dilutions depended on the particular salivary samples taken and were determined by prior experimentation.

Number of experimental sessions

An experimental session ranged in length 13–30 min. Generally, sessions were performed on separate days; occasionally, two were given on one day. A subject began testing by attempting to discriminate between 3 mM NaCl and water. After several sessions, stimulus learning resulted in the subject being able to discriminate perfectly. Therefore, the NaCl concentration was lowered to maintain stimulus confusability. After further sessions, the NaCl concentration had to be lowered still more. This process continued until 'plateau' performance was reached and data could then be collected. These earlier practice sessions were attenuated so that only portions 1 and 2 were performed.

Subject SS performed 41 practice sessions, while KH performed 8, FH: 8, RS: 11. The large number of practice sessions for SS occurred because her testing was spread over a year with breaks in between.

The final NaCl concentration reached by SS was 0.50 mM. At this concentration, data were collected for 60 sessions, corresponding to 720 triangle and 718 3-AFC tests (two missing), 480 sequences for studying sequence effects and 480 measures of physical signal strength. The other three confirmatory subjects each performed 20 sessions at their final concentration (KH, 0.65 mM; FH, 0.80 mM; RS, 0.35 mM).

Results and discussion

The results of subject SS are presented first, with those of KH and FH providing confirmation. The results of subject RS are discussed later because of his different search strategies (decision rules).

Comparison of performance for the triangular and 3-AFC methods

For subjects SS, KH and FH the proportions of triangles and 3-AFCs performed correctly are given in Table I. It can be seen that for all subjects, a higher proportion of 3-AFCs were performed correctly than triangles. This result was significant using the binomial

Table I. Proportion of triangles and 3-AFCs performed correctly

Subjects	% of tests performed correctly		Bionomial comparison of proportions significance level (2-tailed)	Number of tests (triangle or 3-AFC) performed
	Triangle	3-AFC		
SS	50.4	75.1	$P < 0.00006$	720 triangle 718 3-AFC
KH	43.3	67.1	$P < 0.00006$	240 of each
FH	41.3	61.7	$P < 0.00006$	240 of each

Table II. The d' values obtained from proportion of correct triangles and 3-AFCs

Subjects	% of tests performed correctly		d' values (normal)		Confidence interval (%)
	Triangle	3-AFC	Triangle	3-AFC	
SS	50.4	75.1	1.47	1.43	40
KH	43.3	67.1	1.07	1.13	50
FH	41.3	61.7	0.95	0.95	30

d' values obtained from Frijters *et al.* (1980).

Table III. R-indices (as percentage probabilities) giving relative detectabilities of NaCl or water dependent on whether the preceding stimulus was NaCl or water

Preceding stimulus	Target stimulus	Subjects		
		SS	KH	FH
W*	S	76.8^{a}	68.0^{d}	83.0^{g}
S	W	56.7^{b}	61.3^{de}	84.1^{g}
W	W	58.7^{b}	51.6^{ef}	78.5^{g}
S	S	50.0^{c}	50.0^{f}	50.0^{h}

*W indicates the water stimulus, S the NaCl stimulus.
R-indices with the same superscripts are not significantly different ($P > 0.05$).

comparison of proportions. The same result was obtained when triads with salt as the odd stimulus or with water as the odd stimulus were analysed separately. Thus, the paradox of discriminatory non-discriminators was confirmed, along with Thurstonian predictions.

Consistency of d' values obtained for triangle and 3-AFC methods

The d' values were obtained from Frijters *et al.* (1980) for triangles and 3-AFCs are given in Table II. The values are not significantly different, falling at least within each other's 50% confidence interval ($P \geq 0.5$), demonstrating internal consistency for the tables of d'. These results are confirmed with slight variation in confidence interval ($P \geq 0.4$) by other univariate tables of d' (Frijters, 1982; Ennis, 1993). The fact that the same d' was obtained using different test procedures suggests that the decision rules or strategies hypothesized by Frijters (1979a) for the 3-AFC and the triangular methods were correct for these subjects.

Table IV. Proportion of triads performed correctly with NaCl as the odd stimulus versus water as the odd stimulus

Subjects	% of tests performed correctly		Binomial comparison of proporitons significance level (2-tailed)	Number of triadic tests (NaCl odd or water odd) performed
	NaCl as odd stimulus	Water as odd stimulus		
SS	67.0	58.4	$P = 0.0006$	719 of each
KH	56.3	54.2	$P = 0.62$	240 of each
FH	61.3	41.7	$P < 0.00006$	240 of each

Relative detectabilities of NaCl and water stimuli dependent on whether the preceding stimuli were NaCl or water

Table III gives R-index signal detection measures (O'Mahony, 1992), indicating the relative detectabilities of NaCl or water tasted after NaCl or water. Rank sums tests (O'Mahony, 1988) were used to determine significant differences. It can be seen that although the common trend (W-S > S-W > W-W > S-S) is followed on average, there is considerable variation between subjects, regarding significant differences, in the relative detectabilities. This confirms earlier work (Vié and O'Mahony, 1989). This necessitated a separate Sequential Sensitivity Analysis being required for each subject; the analyses were performed in the usual way (O'Mahony and Odbert, 1985; O'Mahony and Goldstein, 1986; Vié and O'Mahony, 1989).

Sequential sensitivity analysis (SSA) predicted that subjects SS and FH would perform a higher proportion of correct triads when NaCl was the odd stimulus. The prediction was clear, so significant differences would be expected. However, for subject KH the same trend was predicted, but more marginally. In this case, the difference might or might not be significant.

Comparison of performance on triads with NaCl as the odd stimulus versus triads with water as the odd stimulus: confirmation of SSA predictions

Table IV gives the proportion of all triadic tests (total of 3-AFCs and triangles) performed correctly when NaCl was the odd stimulus and water was the odd stimulus. As predicted by SSA, subjects SS and FH performed a significantly higher proportions of correct tests when NaCl was the odd stimulus. For subject KH, the same trend was suggested, but not significant. This confirms SSA predictions. When the analysis was performed separately for 3-AFCs and for triangles, the same results were obtained, except for subject SS in the triangle condition, where no significant difference was found. Overall, SSA provides a descriptive explanation for differences in performance when NaCl or water provide the odd stimulus in the triad. Stillman (1993) found a similar result using party dip stimuli with added NaCl but did not invoke SSA as an explanation.

Effects of position bias

For the triangles and 3-AFCs, the data were examined for position bias, namely, to see whether subjects had a bias towards picking the first, second or third stimulus in the triad. Table V indicates the frequency of choice of target stimulus by the subjects in each of the three positions. It can be seen that subject SS had a consistent bias toward

Table V. Frequency of choice of stimuli in the first, second and third position in the triads for 3-AFCs and triangles

Subjects	Test	Number of times stimulus was chosen in given position			Number of tests performed	Chi-square significance level
		1st	2nd	3rd		
SS	Triangle	203	230	287	720	$P = 0.0005$
	3-AFC	213	228	277	718	$P = 0.009$
KH	Triangle	85	65	90	240	$P = 0.1$
	3-AFC	85	85	70	240	$P = 0.4$
FH	Triangle	98	85	57	240	$P = 0.004$
	3-AFC	87	84	69	240	$P = 0.3$

choosing the third stimulus. The bias was significant for both triangle and 3-AFC tests, but was stronger for the former. Subject KH has no consistent position bias, while subject FH had a consistent bias towards picking the first stimulus, which was only significant for the triangle test. Frijters (1977) found positional bias with olfactory stimuli only when stimuli were indiscriminable; that is not the case here.

Given that position bias would increase errors in the performance of the tests, stronger bias in the triangle condition for subjects SS and FH, would tend to enhance the Thurstonian prediction of better performance for 3-AFCs. Yet, position bias does not replace the Thurstonian explanation, because subject KH, with little or no position bias, had a greater discrepancy between performance on 3-AFC and triangle tests than FH (see Table I).

Position bias would also be expected to interfere with the predictions of SSA. As noted in the previous section, SSA predictions for subject SS broke down for the triangle test, where position bias effects were stronger. However, position bias was even stronger for subject FH in the triangle condition and the SSA prediction held. Thus, it would seem that position bias does not furnish a complete explanation for any breakdown of the SSA predictions.

Lability of sequence of relative detectabilities of NaCl and water stimuli dependent on whether the preceding stimuli were NaCl or water

Table III gave R-index signal detection measures, indicating the relative detectabilities of NaCl or water after tasting NaCl or water. These were used to predict relative performance on triangles and 3-AFCs for triads with NaCl as the odd stimulus versus water as the odd stimulus. The order of detectabilities given in Table III indicate mean values for each judge taken over the whole experiment. However, as the subject progressed through the experiment, it was to be expected that as a result of stimulus learning, the order of detectabilities would change. To investigate this, subject SS was chosen because she provided a substantial amount of data. Table VI indicates the order of detectabilities for her first 30 sessions versus her second 30.

The order changed over time, the overall order being more strongly a result of the first thirty sessions. As the experiment proceeded, the subject's performance on the S-S sequence (noise) improved, lowering the (relative) R-index scores for the other sequences. This confirmed earlier observations on the effects of learning (O'Mahony

Table VI. R-indices (as percentage probabilities) giving relative detectabilities of NaCl or water dependent on the preceding stimulus for the initial and final sessions performed by subject SS

Preceding stimulus	Target stimulus	First thirty sessions	Final thirty sessions	Overall
W*	S	76.3^{a}	77.9^{d}	76.8^{f}
W	W	65.0^{b}	53.1^{e}	58.7^{g}
S	W	64.9^{b}	50.0^{e}	56.7^{g}
S	S	50.0^{c}	50.0^{e}	50.0^{h}

*W indicates a water stimulus, S a NaCl stimulus.

R-indices with the same superscripts are not significantly different ($P > 0.05$).

and Goldstein, 1987). It also altered predictions about the relative performance of subject SS for triads where NaCl or water was the odd stimulus. For the first 30 sessions, performance with NaCl as the odd stimulus was superior, as would be predicted (71.3% correct versus 59.3%; binomial comparison of proportions, $P = 0.0006$). For the last 30 sessions, the changed order of detectabilities would give a prediction of no difference in performance on triads with NaCl or water as the odd stimulus. The data were consistent with this (62.8% versus 57.5%; $P = 0.13$).

O'Mahony and Goldstein (1987) managed to train a subject so that there was no significant difference in the order of detectabilities. The training consisted of tasting all four sequences with feedback for a total of 7.3 h. In spite of extensive testing (approximately 20 h), subject SS did not achieve this. However, she was not given specific training nor was she given feedback. This may illustrate the relative efficacy of incidental learning versus targeted training.

Stimulus learning during practice sessions

The ability of the subjects to distinguish lower and lower concentrations of NaCl from water as the practice sessions progressed, deserves comment. The data have been given above. Presumably, this was the result of some form of long term stimulus learning. It was certainly distinct from the more transient warm-up effect (O'Mahony *et al.*, 1988). The mechanism of such stimulus learning is unknown. One hypothesis is that it involves a 'hardwiring' of the warm-up mechanism, which itself is hypothesized to be due to selective attention. Another possibility is the recruitment of more units of the taste system, whether these be receptor sites or more central entities. An understanding of such perceptual learning is important for the training of expert tasters in the sensory analysis of food.

Secreted salivary NaCl concentrations

At five points throughout the experimental sessions, saliva samples were taken to monitor the secreted salivary NaCl concentrations. The authors are aware that these concentrations are affected, albeit minimally, by residuals from prior tastings (O'Mahony, 1979; O'Mahony and Goldstein, 1987), but it may be assumed that they are sufficiently related to be able to pick up any gross changes or trends in secreted salivary NaCl. Because mouth movements continued during the collection period, these samples were not resting saliva samples. The saliva values are given in Table VII.

From the table there was no systematic trend for gradual increase or decrease in

Table VII. Mean salivary NaCl concentrations (mM) collected at five points during the experimental session

Subjects	Saliva samples				
	1	2	3	4	5
SS	7.5^{a}	10.0^{b}	8.7^{c}	8.0^{ac}	8.7^{c}
KH	3.0^{d}	5.2^{e}	4.8^{e}	5.3^{e}	5.5^{e}
FH	6.9^{f}	3.9^{g}	3.5^{gh}	3.6^{gh}	3.1^{h}

The same superscripts denote means that are not significantly different ($P > 0.05$).

Table VIII. Mean changes in Na^+ concentration (mM) upon tasting NaCl or water stimuli, indicating physical signal strengths

Subjects	Stimulus					
	NaCl			Water		
	Mean	Standard deviation	Number of samples analysed	Mean	Standard deviation	Number of samples analysed
SS	0.26	0.27	240	−0.27	0.27	240
KH	0.30	0.30	80	−0.30	0.31	80
FH	0.44	0.44	80	−0.44	0.44	80

salivary NaCl during the session. For subjects SS and KH, the first salivary samples contained lower concentrations of NaCl. It can be hypothesized that the result of the oral movements required by the experiment stimulated salivary flow, thus increasing secreted salivary NaCl concentrations. Yet, the reverse was the case for subject FH. In his case, it may be hypothesized that his oral movements did not stimulate salivary flow sufficiently to give an increase in NaCl concentration. Furthermore, he was observed not to be a thorough expectorator. The major effect, then, could have been due to the dilution of secreted salivary NaCl by the lower concentration NaCl and water stimuli used during the experiment, thus reducing NaCl concentrations.

Comparison of performance on triads with NaCl as the odd stimulus versus triads with water as the odd stimulus: examination of physical signal strengths and test of Thurstonian modeling predictions

As mentioned above, the current model of NaCl taste adaptation (McBurney and Pfaffmann, 1963; Bartoshuk *et al.*, 1964; Bartoshuk, 1968, 1974, 1978, 1980) considers physical signal strengths of NaCl and water stimuli to be given by the change in concentration from the adapting concentration. Because the NaCl concentrations encountered in the present experiment were low (comparable to secreted saliva values), it may be assumed that adaptation was rapid and complete (to tastelessness). This was strongly supported by subjective reports. Therefore, it was reasonable to take the change in concentration upon tasting a given stimulus as the physical signal strength of that stimulus. The authors are aware that any concentration changes in the immediate vicinity of the taste receptor membrane due to surface effects (Price and DeSimone, 1977) could cause differences from the concentration in the bulk of the saliva.

Accordingly, changes in concentration upon tasting given stimuli, were measured for NaCl and water stimuli. For the former, the change was generally an increase in NaCl concentration and for the latter, a decrease. Table VIII gives the mean changes for each subject along with their standard deviations. It can be seen that the data are remarkably symmetrical; the mean increase in NaCl concentration upon tasting NaCl stimuli being equal to the mean decrease in NaCl concentration upon tasting water stimuli.

A Thurstonian explanation for triads with one NaCl stimulus eliciting better performance from subjects than triads with one water stimulus, involves a consideration of perceptual variance. It postulates that if the perceptual variance of one stimulus is greater than that of a second stimulus, then performance on triads involving only one of the stimuli with the greater variance would be superior. Simply, a triad with two stimuli from the distribution with greater perceptual variance has a greater chance of the two stimuli being judged as dissimilar, thus eliciting more errors and inferior performance. Therefore, if the NaCl stimulus has a greater perceptual variance than the water stimulus, performance on a triad with one NaCl stimulus will be superior to performance on a triad with one water stimulus. In this study, the performance for triadic tests was indeed superior when NaCl was the odd stimulus. For this to be explained by Thurstonian modeling, the perceptual variance for NaCl would have to be larger than the perceptual variance for water stimuli.

There is no direct way of measuring perceptual variance. However, the variance in physical signal strength for the NaCl and water stimuli are given in Table VIII. Although these are not the same thing, it is reasonable to hypothesize that they should have some correspondence. An exact correspondence, namely a larger physical signal strength variance eliciting a larger perceptual variance would be the most agreeable hypothesis. It would be analogous to saying that the more a volume switch on a radio is turned, the greater would be the variation in perceived sound intensity. In Table VIII, the physical signal strength variances were equal for both NaCl and water stimuli. This suggests that the Thurstonian model for superior performance on triads with one NaCl stimulus may be less likely to be true than the SSA explanation, detailed above.

To argue, albeit with less parsimony, for the Thurstonian explanation would require a postulate that equal physical signal strength variances produced unequal perceptual variances. Such an argument would require that the noise or neural variance for the transmission of signals in the sensory system (transduction, neurons, central processing) for NaCl stimuli was greater than that for water stimuli; this hypothesis would need independent corroboration.

It is also possible to examine the relationship between perceptual variance and variance in physical signal strength by examining d' values. From Table VIII, a d' for physical signal strength can be obtained from each judge by dividing the distance between the mean physical signal strengths by the standard deviation. In all cases, $d' = 2.0$. From Table II, perceptual d' values range from 0.87 to 1.47. Perhaps the simplest explanatory hypothesis would be that the perceptual system is noisy and adds variance. This would be represented in Thurstonian terms by the perceptual distributions having greater standard deviations and overlapping more than the distributions for physical signal strengths. It is interesting to note that while the physical signal strength d' was the same for all judges, the perceptual d' was not. This would suggest that subjects varied in

Table IX. Inconsistent data of subject RS

Proportion of triangles and 3-AFCs performed correctly

% of tests performed correctly			Number of tests
Triangle	3-AFC	*P**	(Triangle or 3-AFC) performed
47.1	54.2	0.099	240

Proportion of triads performed correctly with NaCl as the odd stimulus versus water as the odd stimulus

NaCl as odd stimulus	Water as odd stimulus	*P**	Number of triadic tests (NaCl odd or water odd) performed
53.8	47.5	0.14	240

The *d'* values obtained from proportion of correct triangles and 3-AFCs (from Frijters *et al.*, 1980)

d' values (normal)		
Triangle	3-AFC	*P***
1.31	0.69	<0.001

R-indices indicating relative stimulus detectabilities of NaCl or water dependent on whether the preceding stimulus was NaCl or water

W-S	S-W	W-W	S-S	*P***
67.7^a	49.5^b	48.5^b	50^b	<0.01

**P* = significance level from binomial comparison of proportions.
***P* = significance level derived from d' confidence limits.
****P* = significance level from Rank Sums Test.
R-indices with the same superscripts are not significantly different ($P > 0.05$).

the relative noise levels of their perceptual systems, with FH having a 'noisier' system than KH.

Search strategies and decision rules: different decision rule for subject RS

The data for subject RS are given in Table IX. They differ from the other three subjects. Although the trends for performing better for the 3-AFC than the triangular method and performing better when NaCl was the odd stimulus are evident, they are not significant. Furthermore, *d'* values obtained from 3-AFC and the triangular methods do not correspond. Evidently, subject RS was not performing in the same way as the other three subjects.

The other three subjects, when interviewed about their search strategies during testing, indicated that they had used the 3-AFC and triangle decision rules or strategies, as given in the instructions. However, subject RS did not and it is here that the discrepancy would seem to be introduced. RS reported that for him, NaCl tasted after water (W-S) was a particularly noticeable stimulus and that he used this signal as much as possible in his discrimination tests. If he was not mistaken, this would generally indicate the identity of two stimuli in the triad (it could sometimes indicate the identity of all three stimuli or only one.

This report is certainly consistent with the R-indices indicating RS's relative stimulus detectabilities in Table IX. They show that the W-S detectability was significantly greater, while the others were not significantly different. From this, an SSA analysis would predict that his performance on triads with NaCl as the odd stimulus and triads with water as the odd stimulus would not be significantly different. Table IX confirms this. It is worth noting that the variances in his physical signal strengths were equal so that Thurstonian modeling would also predict the same result.

RS performed better for the 3-AFC than the triangular method, but the effect was not as pronounced as with the other subjects. He reported that for 3-AFCs, he merely identified the W-S sequence which gave him the knowledge of the identity of two stimuli (sometimes one). The additional information given in the instructions for the 3-AFC (numbers of NaCl and water stimuli present) would allow him to determine the identity of the other stimuli in that triad. This is different from the regular 3-AFC strategy used by the other three subjects. For triangles, however, RS reported that he used something like the regular triangle strategy. His approach was to identify the W-S sequence and determine whether the third stimulus was more similar to the NaCl or water.

RS's lack of difference in performance between 3-AFC and triangle tests either means that he performed worse than expected on the 3-AFC tests or better than expected on the triangle tests. If the former were true, it would mean that his 3-AFC strategy of searching for the W-S sequence and deducing the third stimulus was inferior to the regular 3-AFC strategy. Perhaps the regular 3-AFC strategy is more robust in that it requires attention to be paid to all three stimuli in the triad, rather than concentrating on just the W-S stimuli.

The alternative explanation for the discrepancy is that RS performed better than expected on the triangle test. This would not be likely if RS had adopted the regular triangle strategy. Yet, it is possible, despite his subjective reports, that his tendency to look for the W-S sequence might trigger him into using a completely different strategy that could result in superior performance. Such a strategy is considered later.

The d' values obtained from 3-AFC and triangle tests do not agree (Table IX). This inconsistency is to be expected when a subject does not use the decision rules postulated by Frijters (1977). The data from RS introduce the importance of control of the decision rule or strategy used in a discrimination test. Just because a subject is instructed to use a particular strategy does not mean that he will necessarily do so. The first three subjects (SS, KH, FH) reported that they used the strategies they were instructed to use; subject RS reported that he adopted a novel strategy at least for the 3-AFC test. Accordingly, d' values for 3-AFC and triangle tests corresponded for the first three subjects; for RS, they did not. It is also possible that subjects, despite their reports, used mixtures of strategies. The first three subjects may sometimes have switched to RS's strategy and vice versa. Yet, it is to be assumed that the first three subjects generally maintained the appropriate search strategies because their d' values corresponded.

Little research has been done into the decision rules or strategies used in discrimination testing. However, observations in the authors' laboratory have indicated that subjects do not always adopt the search strategies given in instructions. This has importance in determining whether subjects can discriminate significantly between two stimuli.

Tables of *d'* assume that subjects maintain a particular decision rule; a new decision rule requires new tables.

Strategy change is also an important consideration. Consider a subject performing a triangle test. Should only the three triadic sequences involving one NaCl and two water stimuli be presented, then it is possible that with repeated testing, the subject could notice this and switch his strategy to the 3-AFC. The proportion of tests he would perform correctly would increase, which would give misleading results. Certainly, it would result in the choice of the wrong *d'* tables. Naturally, this argument applies to taste and flavor discrimination in general, not just NaCl versus water discrimination. It is interesting to note that the A.S.T.M. Manual on Sensory Testing Methods (1968) recommended the use of just three triadic sequences for the triangle test, thus allowing the possibility of inadvertent strategy change. This has been discussed by Frijters *et al.* (1982) and would also furnish an explanation for McBride and Laing's (1979) incidental training effect.

It is logical that, given information about the nature of the stimuli, a subject could switch from a triangle to a 3-AFC strategy. If the subject was not given such information, it would not seem possible for the subject to switch. Yet this is not entirely true. An experienced subject who has a good memory for the stimuli involved, could use a two-part strategy, one part of which involved a 3-AFC decision rule. Consider a subject who performed a triangle test involving NaCl and water stimuli. Because of the instructions given to him, he would not have known the number of each stimulus present (one NaCl or one water). It is possible that he could taste all three stimuli and then hypothesize whether the triad contained one NaCl or one water stimulus. Having ascertained this, he could then operate a 3-AFC strategy (e.g. look for the saltiest stimulus), rather than a triangle strategy (comparing distances to determine the most different stimulus). RS reported that he sometimes adopted this strategy, which could have given him better than expected performance on his triangle test. Similarly, the other subjects reported occasionally using this strategy, presumably not as often as RS. Once again, strategy change would seem to be an important, albeit unresearched, variable in discrimination testing.

Re-evaluation of physical signal strengths

In Table VIII, the physical signal strengths were considered for the two stimuli, NaCl and water. This gave two distributions which were used as the basis for a classical Thurstonian modeling approach. However, a closer examination of the physical signal strengths would suggest the presence of more than two distributions. Logically, this experiment could yield eight distributions. There could be four distributions for NaCl; there could be separate distributions for NaCl tasted after water (W-S) and NaCl tasted after NaCl (S-S). These, in turn, could be split into two further distributions, depending on the stimulus which preceded each of these stimulus pairs. This would result in four distributions, one for each of the following sequences: W-W-S, S-W-S, W-S-S, S-S-S. Similarly, the water distribution could be split into four: W-W-W, S-W-W, W-S-W, S-S-W. The means of these eight distributions were computed and were subjected to ANOVA and LSD testing. It was found that they separated into just three distributions: one for W-S, one for S-W, and a third for W-W and S-S combined ($P < 0.05$). This

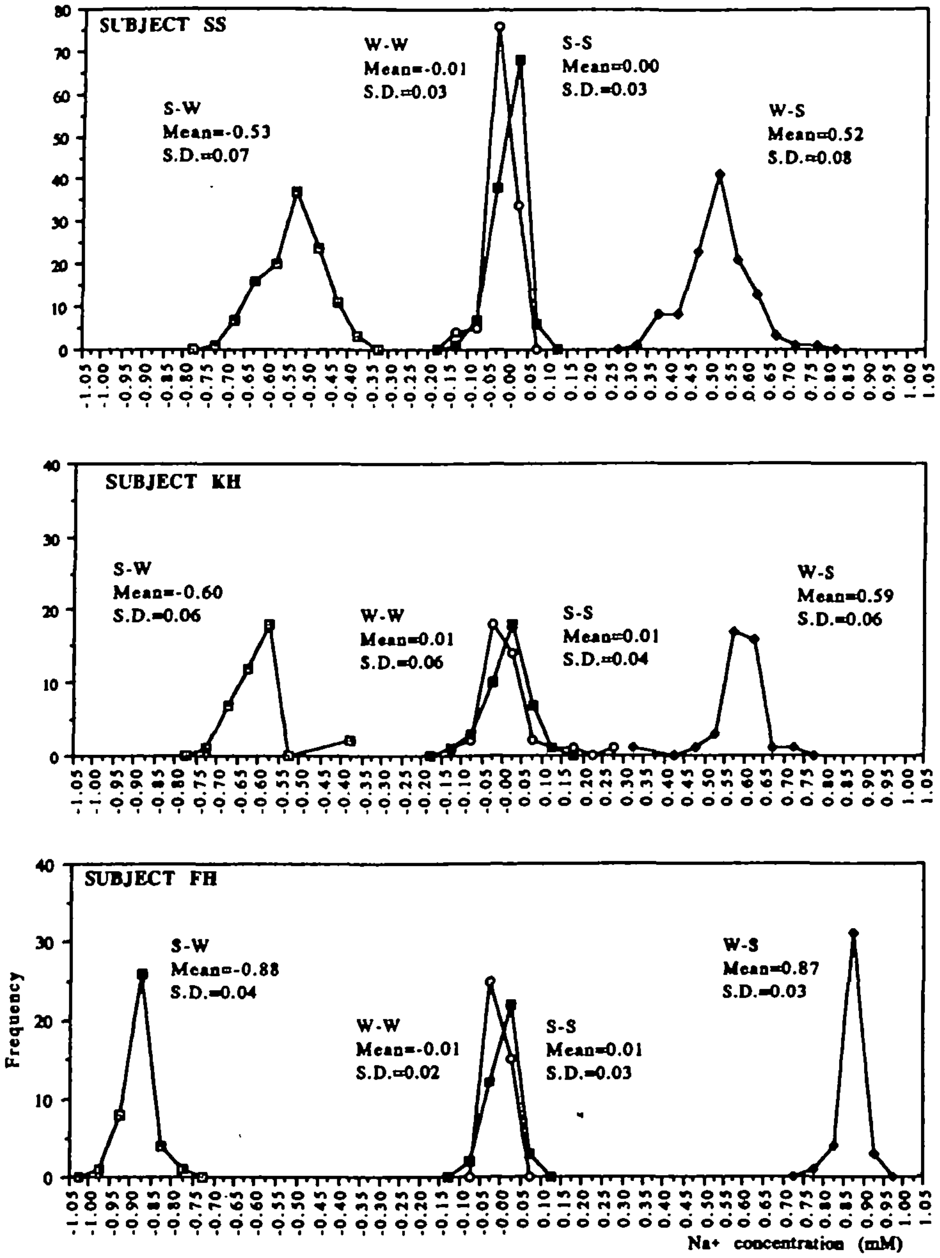

Fig. 2. Representation of physical signal strengths for NaCl and water stimuli dependent on whether the preceding stimulus was NaCl or water.

is more simply visualized as four distributions, for which the latter two overlie each other. These are illustrated in Fig. 2 and their parameters are given in Table X.

From Table X, it can be seen that the S-W and W-S distributions are fairly symmetrical

Table X. Mean changes in Na^+ concentration (mM) upon tasting NaCl or water stimuli, tasted either after prior NaCl or water stimuli, indicating four possible signal strengths

Subjects	Stimulus								No. of samples analysed
	S-W		W-W		S-S		W-S		
	Mean	*SD	Mean	SD	Mean	SD	Mean	SD	
SS	−0.53	0.07	−0.01	0.03	0.00	0.03	0.52	0.08	120**
KH	−0.60	0.06	0.01	0.06	0.01	0.04	0.59	0.06	40
FH	−0.88	0.04	−0.01	0.02	0.01	0.03	0.87	0.03	40***

*SD implies Standard Deviation.

**For S-W and W-W, 119 samples were analysed.

***For S-S and W-S, 39 samples were analysed.

about the zero for physical signal strength. The W-W and S-S distributions are centered around the zero, the S-S distribution tending towards slightly positive means, W-W tending towards slightly negative means. The W-S and S-W distributions of physical signal strength do not overlap. Yet, because these two can be confused psychophysically, the sensation distribution must do so. As far as any modeling is concerned, the four psychophysical distributions would need sufficient overlap to account for confusions between stimuli. Probably, the sensory system adds noise. The same argument has been advanced above for the two distribution model, with a consideration of physical and psychophysical *d'* values.

The presence of four physical distributions, albeit two overlying, suggests the classical two distribution Thurstonian approach did not apply here. Yet, the quoted d' values from the 3-AFC and triangle test tables, computed using this classical approach, did correspond. If the four distributions were to be reduced to two distributions, they would be bimodal, not normal. Therefore, the *d'* values given in the tables would be incorrect. However, it is still possible for such incorrect *d'* values to correspond.

The presence of more than two distributions creates a problem for the classical Thurstonian approach. There is now more than one *d'* value to be considered. Thus, Thurstonian modeling must be extended to account for this. The degree of difference must be expressed using a parameter other than a simple *d'*.

It could be argued that these three or four distributions reduce to two perceptually. Yet this does not correspond to subjective reports of the sensation qualities encountered for these stimuli. The W-S sequence tended to give a taste sensation indicating the presence of low concentration NaCl, while the S-W sequence tended to give a distilled water taste. The S-S sequence tended to give a tasteless sensation, while W-W gave a tasteless sensation, but the tastelessness was distinct from the tastelessness experienced with S-S; this confirms earlier reports (O'Mahony, 1973). This suggests four distributions perceptually, more than the three encountered for physical signal strengths. Modeling of these results will indicate the truth of this prediction.

Although the physical signal strengths separated into three distributions for the three subjects SS, KH and FH, it does not mean that this will be true for all subjects. Subject RS had six distinct distributions according to ANOVA ($P < 0.05$). This suggests the possibility of an eight distribution model for some subjects for which various distributions will overlie one another, depending on the oral environment of the particular subject.

General discussion

Classical Thurstonian modeling, involving two distributions was developed for visual stimuli, where there are no carry-over effects from stimulus to stimulus. When Ura (1960) first applied what should strictly be called Thurstone–Ura models to 2-AFC, triangle and duo-trio discrimination tests for the food and brewing industries, he omitted to take into consideration carry-over effects, such as those occurring in the tasting of foods and beverages. Whereas these may be ignored for visual stimuli, they are important here. Frijters' (1977) results indicate that they were not important for the olfactory stimuli used in his study. Yet, more research is required. Even for taste, carry-over effects can vary in importance with the particular experimental protocol used (O'Mahony and Wingate, 1974; O'Mahony and Heintz, 1981; Riskey *et al.*, 1979). They have been shown to be sufficiently important for discrimination testing that a model, sequential sensitivity analysis (SSA), was based entirely on them. The present study suggests that carry-over effects might be modeled into a Thurstonian framework by considering more than two distributions. The stronger the carry-over effects, the greater the number of distributions that would be required. In essence, the use of more than two distributions introduces SSA concepts into Thurstonian models.

It would seem that the two distribution Thurstonian model involving a simple *d'* value no longer applies. A Thurstonian model based on more than two distributions could be developed. With the four distributions available in the present experiment for triadic testing (W-S, S-S, W-W, S-W), the momentary intensities of the stimuli in the triad can be chosen from two or three of these distributions. In the case of the triangular method, choosing momentary intensities from two distributions would require the classical Thurstonian treatment. Choosing momentary intensities from three distributions is equivalent to treating all three stimuli in the triad as different; this type of model and its implications for triadic choice will be discussed by the authors in a future paper (Ennis and O'Mahony, 1994).

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