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Short heading

Normed discrimination across the senses

Insight into sight, touch, taste and smell by multiple discriminations from norm

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Abstract

The paper presents an innovative theory of perception of multiple features across and within modalities. Each step is illustrated by an aspect of data from diverse experiments. The theory is that a template or norm of previously configurated features is used to perceive an object in a situation, such as consuming an item of food or drink. A mouthful usually stimulates sight first and then touch, taste and smell, with thermal, irritative, kinaesthetic and auditory patterns often also involved. The visual information also typically includes meanings of words, numbers and pictures. Attended sensory and symbolic features of the situation are integrated by the individual into a multidimensional distance from the norm. Dimensions are calibrated in units of the response's discrimination between levels of each stimulus feature. This approach to perceptual performance is expounded for sensed and/or conceived visual features of drinks and foods, and their tasted or smelt constituents or felt and heard cracking during a bite. In addition, the conceptual process that informs an analytical judgment can influence another judgment. Applying the concept to a stimulus forms a descriptive process. A concept may also be applied to another concept or to a description, giving greater depth of meaning to an integrative judgment. Furthermore, a description can be applied to an environmental source of stimulation, creating a percept that presumably is conscious, whereas unconceptualised stimulation may be subconscious.

Keywords

Sight and oral senses. Sensory and symbolic perception. Perceived eating. Foods sensed and conceived.

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Introduction

The perceiving of entities having multiple sensory features requires mechanisms that coordinate those features within their wider context. An innovative combination of classic ideas in psychology can characterise such mechanisms by simple exact calculations of interactions among the psychophysical relationships of an individual's judgments to variations in the features of a situation (Booth & Freeman, 1993). The approach is illustrated here by cases of perception by sight and the oral senses, as a contribution to the Special Issue of *Seeing and Perceiving* on “Multisensorial Perception.” The paper goes stepwise through a formulation of the complete theory of normed multiple discriminations. Each step exemplified by a set of data of the simplest feasible sort. Experimental details that may be important in other approaches are omitted if irrelevant to the present approach, in order to simplify the presentation. At the end of the paper, this psychological approach is briefly put into the context of both physical and social approaches to the perceived environment.

The theory starts with the assumption that, for each object in its context, perceptual judgments are made relative to a multi-featured norm laid down in long-term memory by previous experience (compare Stewart, Brown & Chater, 2005). In research on the recognition of physical objects, the mental representation of the object and situation called a ‘norm’ here has also been termed the *Gestalt* or a ‘template’ (e.g. Lockhead, 1992; Liu, Kersten & Knill, 1999; Liu, Knill & Kersten, 1995).

Attended features of the object and context are integrated by the individual into a multidimensional distance from that norm. That is, the norm is a mental reference point or internal standard, having the coordinates (0, 0, 0, …). The psychological distance on each dimension is measured in units of the discrimination by the quantitative judgment between levels of the environmental source of perceived stimulation (Booth, Thompson & Shahedian, 1983; Conner, Haddon, Pickering & Booth, 1988b). That is, a dimension in the geometrical model is a discriminal process (Thurstone, 1927) achieved by the individual perceiver, consciously or unconsciously. In the terminology of J.J. Gibson (1979), each dimension represents a category of affordance by the physical environment that is being discriminated by the perceptual judgment.

Vision science has direct parallels to some aspects of this approach. Dimensionality of coding accounts for the differences between chromatic and scotopic vision in the perceiving of colour mixtures (Pugh, 1988). More recently, internal standards have been found to give greater precision than the traditionally used external standards (Morgan, Watamaniuk & McKee, 2000; Nachmias, 2006).

The norm is often (or may always be) a configural conditioned stimulus, i.e. some form of learnt percept. Current theory of the associative processes in configural conditioning deals solely in categorical stimuli, with no regard for the strengths of their components (Pearce, 1994). Nevertheless there is evidence from the human species and other mammals for the associatively conditioned configurating of a flavour category with the quantity of a visceral stimulus that changes during a meal such as gastric distension (Gibson & Booth, 2000; Kissileff, Booth, Thornton *et al*., 2008) or between meals such as lack of essential amino acids (Gibson, Wainwright & Booth, 1995). With regard to a simple quantitative stimulus, rats can be associatively conditioned to prefer a low level of sweetness, whereas before learning they had only the reflex of 'the sweeter the better' (Booth, Lovett & McSherry, 1972; cf. Booth, Higgs, Schneider & Klinkenberg, 2010). Implicit memories integral to perception have been proposed for the sense of smell (Stevenson & Boakes, 2003; cp. Booth, 1995). The present theory invokes such learnt norms for all the senses. Perceiving is analysed as an individual's momentary discrimination between the levels of features at the implicitly remembered norm point and the levels in the environment of the features currently being processed (Booth & Freeman, 1993).

The examples of normed multiple discriminations in this paper come from particular situations in which an item of food or drink is consumed, by itself or as part of a meal or snack. The sequence in which the eating and drinking of a mouthful of the item starts to stimulate the senses is usually sight first (sometimes with orthonasal smell) and then touch, taste and retronasal smell, with thermal, irritative, kinaesthetic and auditory patterns often also being involved. The visual information typically includes meaningful words, numbers and pictures as well as shapes, sizes, surface textures, colours and other physical features of the item. That is, normed discrimination theory covers symbolic or conceptual stimuli as well as material or sensory stimuli (Booth & Freeman, 1993). Hence the examples in this paper include either or both sensory and conceptual features of uses of items of food or drink.

It should be emphasised that this paper is not a review of multisensory research on foods and drinks. Many investigators, including ourselves, have studied perceptual interactions between tastants, odourants and colourings, and among tastants only or odourants only. Yet those experiments were not designed nor were their data analysed as required by the theory of normed multiple discrimination and so they are not considered here.

The findings quoted in this paper are from experiments involving two or more sensory and/or conceptual visual features or the orosensory features of two, four or five tastants or odourants in familiar foods or beverages, or multiple patterns of felt and heard cracking of a solid food. The materials and their labelling were experimentally designed to vary within a personally acceptable range during the session of testing. The perceptual judgments were anchored on either the usual version of the test items or the participant's most preferred version.

The initial work on normed discrimination was on a single gustatory feature within a familiar context, either sucrose or sodium chloride varied within an otherwise constant formulation of the liked food or drink (Booth *et al*., 1983; Conner & Booth, 1988; Conner *et al*., 1986, 1987, 1988a,b). One experiment was done on a colouring, although the raw data accumulated judgments across participants and so the theory of the individual's discriminative performance was applicable indirectly only (Conner, Pickering, Birkett & Booth, 1994). Nevertheless there was visual input during all those experiments: each sample of test material was viewed before it was assessed. Subsequent work across the senses has shown the importance of that visual context of the features varied in other modalities.

'Framing' through sight was a key to the success of a recent experiment on sensual pleasure induced by the innate reflex to sweetness, contrasted with the learnt motivation from sweetness as identified by normed discrimination (Booth *et al*., 2010). Linearity of deviations from the personally ideal sweetness for apple juice was crucial to the economy of the design. That straight line through the ideal point depended on an ideal context, including the sight of the suspended particles from pressed apples as distinct from the less attractive clear fluid of brands made from filtered or evaporated and reconstituted juice.

Multiple discriminations from norm

Multimodal and multi-featured

There is some ambiguity in the term 'multisensory.' The recently dominant use refers to experiments coordinating at least two sensory modalities. These might be vision and mechanoreception, or gustation and olfaction. Often, however, only one feature is presented in each modality. For example, the location of an object might be seen and touched. In our research programme, retronasal and orthonasal olfactory discriminations of benzaldehyde were compared using the tasting of sucrose to support perception of an almondy flavour in the test food (Marie, Land & Booth, 1987). Later, visual and tactual discriminations between levels of cream in coffee were compared (Richardson-Harman & Booth, 2006).

However, an older use of the term 'multisensory' refers to two or more categories of stimulus within a single sensory modality. In vision, this might be a submodality such as motion, spatial frequency or colour. Each (sub)modality has distinguishable categories, although their boundaries and number may be contingent on a society's environs and language. Within one of the chemical senses, these categories might be compounds stimulating different receptor types or profiles of receptors, as in taste mixtures (Booth, Konle & Sharpe, 2008; Laing, Link, Jinks & Hutchinson, 2002) or mixtures of odourants (Booth, 1995; Booth, Freeman & Kendal-Reed, 1995; Cain, Schiet, Olsson & Wijk, 1995; Polak, 1973), or indeed wavelengths of light and retinal pigments if colour is considered to be the 'photochemical' sense. The term 'multisensory' is used in this paper in that inclusive sense.

Arguably the description as multisensory, rather than bimodal or multimodal, is better justified if there are at least two features in at least one of the modalities, or perhaps three sensory modalities, such as colour and flavour composed of smell and taste. Nevertheless, even if the consensus restricts 'multisensory' to multimodal experiments, the present approach rests on a split of visual shape perception into two (sub)modalities – material and cultural. If the viewed shapes are geometrical areas or natural volumes, then the modality is visible material characteristics (visual appearance of shape and size). If the shape being seen is a word or sentence, or even just a letter, number or logo, the modality is visually symbolised cultural attributes (the read meaning of the shape or its visually perceived conceptualisation). A picture may be both sensed and read, as we shall see.

As was discovered for colour vision in the 19th century, experimenters on taste and smell are finding that physically specified sources of stimulation do not map simply onto molecularly and physiologically identified sensory receptor mechanisms, let alone onto culturally defined sensory vocabulary. The one-to-one matching of activation of a receptor type and a taste word (as assumed by ideas such as 'basic taste' and 'labelled line') has broken down. One afferent fibre can be activated by different types of receptor (Roper, 2007). Compounds whose taste is recognised as 'bitter' stimulate a large family of receptor types (Caicedo & Roper, 2001; Delwiche, Buletic & Breslin, 2002). There are at least two types of sodium ion receptor that give rise to a single taste agreed to be "salty" (Halpern &

Darlington, 1998). Different acids, and even sugars, may yet be shown to stimulate molecularly distinct sensitivities, despite their afferent patterns controlling the single concepts of “sour” and “sweet” respectively. Also the amino acid ion, monohydrogen L-glutamate, has its own receptor and concept (“savoury”) but different aspects of its across-fibres pattern can also be activated by sweet, bitter and sour receptors (Booth *et al*., 2008; cp. the Land effect for colour recognition). The same sort of signal profiling may occur for touch. Hence the term ‘multisensory’ might best be allowed for any case of two or more identifiable sources of stimulation, across senses or within a submodality.

Multisensorial multiconceptual cognition

On the above theory of perception, the sole issue is how close the sensed and conceptualised features of each particular test sample come to the amounts of those features in the physical and social norm for the context simulated by the experiment for the participant (McBride & Booth, 1986; Booth & Freeman, 1993). This approach raises fundamental issues for research into multisensory perception that some psychologists have begun to address in other ways (e.g., Auvray & Spence, 2008; Prescott, 1999). The present approach investigates variants of a single object within a particular context. The various sensed material factors in each object and situation interact during perception. In addition those sensory factors interact with conceptual attributes of the object and context. Hence if just one taste or texture of a food is being investigated, the measurements need to be made in the usual context of eating (Booth *et al*., 1983; Conner *et al*., 1988a,b). For example, few people have used sugar in plain water as a drink. Hence specifying a preferred sweetness of sugar water is difficult and a usual sweetness impossible. If the water is given the sourness, aroma and colour of a particular fruit, however, the personal ideal point for a sweetener is easily elicited (Booth *et al*., 2010; Conner *et al*., 1986). In contrast, the modelling of interactions between responses made in very general terms such as “taste” and “health” does not make contact with actual influences on action; it merely elicits conventional rationales. A survey can add to scientific knowledge but only if it is designed and interpreted to distinguish between hypotheses drawn from theory established by experimental measurements.

A recent example relates to the practical issue of eating of enough fruit or vegetables each day. Experimental evidence from the first uses of normed discrimination, coupled with questionnaire assessment of preferred variants of foods, indicated two sorts of 'sweet tooth' in British people (Conner & Booth, 1988; Conner *et al*., 1988b). One pattern of integrative judgments had norms of liking fruit and the few sweet vegetables such as carrots. The other pattern of preferences centred on very sweet foods such as chocolate and honey. The UK pattern, at least in those days, has recently found a parallel in the USA: users of sweet snack foods eat more fruit than vegetables that are mostly not sweet (Wansink, Bascoul & Chen, 2006). More detailed information is needed on the sensory and conceptual influences on each act of selecting fruit rather than a packet food between meals**,** or something like ice cream for dessert (Booth & Booth, 2011). Our approach provides such evidence, situation by situation and person by person.

Sensory and conceptual discrimination

Normed discrimination theory spans conceptual as well as sensory features because it depends on the fundamental idea of distinguishing between levels of an environmental quantity, regardless of what phenomenon is measured. Everything in the theory is based on a unit of discrmination of the disparity between two amounts of a source of stimulation (stimulus levels) by a particular amount of intervention on the environment (response score). Both the stimulus and the response could be either material or symbolic.

In the medium range of stimulation to which this theory applies, equal differences in response discriminate sources of material stimulation in equal ratios (logarithmic differences) of the physical measurement of the stimulus. Yet the unit of multiple discriminations cannot be called the Weber-Fechner ratio, because equal differences (intervals) of symbolic stimulation are discriminated by equal response differences (Figure 1). Hence the unit is called the 50%- or half-discriminated disparity (HDD).

The above is what Torgerson (1958) called the objective interpretation of the measure traditionally given the subjectivist name of the 'just-noticeable difference' (JND) between magnitudes of sensation. The terms 'discrimination threshold' or ‘difference limen’ are also used when ignoring the theoretical understanding of signal processing that is familiar from the analysis of detection tasks. The JND and HDD are the same calculation but the concept of ‘discrimination of a disparity’ presumes nothing about the transformations through which information in the observed stimulus goes on the way to producing the observed response. In particular, relations between a single stimulus and a single response do not distinguish between presence and absence of any subjective experience such as a magnitude of sensation. As a matter of logic, such hypotheses about mediating processes can be tested only on data that include at least one additional stimulus or response -- the minimum sets of variables for multiple discrimination scaling.

The working principle that HDDs for symbolic quantities are in intervals, not ratios, follows from what must result in a design with one material input and two outputs. If each of the two quantitative outputs relate log-linearly to the input, i.e. in ratios of the physical measure of the perceived source of stimulation, the outputs must relate linearly (Figure 1). That is, if the concept behind one of those responses influences the other response concept, the HDD for that 'psychopsychical' function must be in equal intervals.

Figure 1 about here

It is important that the HDD is what was discriminat*ed* in a particular input by a specified output within the set of data from an individual during a single session within a normed context. An HDD is not what might be discrimin*able* by the participant in some circumstances. Hence normed discrimination scaling repudiates the traditional preoccupation of psychophysics with a formula to fit the whole range of stimulation in isolated presentations. As was evident from the start in Weber's observations in the 1830s, JND scaling applies only to medium strengths of physical stimuli (Murray, Ross & Weber, 1996). A different function has to take over as receptors approach saturation (Biedler, 1954). The psychophysical function must have yet another shape when the problem changes to detecting whether any stimulation has occurred (Laming, 1986). Ordinary perception deals with situations well away from either detection or saturation. Hence that is the region where a multiple-featured norm will be. The zero for an HDD scale is the norm point for that feature. The object is liable to change category or become unrecognisable if, for example, a visual feature becomes either so weak as to be nearly invisible or so strong as to be almost blinding.

Discrimination scaling also sidesteps the supposed problem of 'grounding' conceptual categories in sensed material characteristics or activations of brain regions (Barsalou, 2008). Interactions among the processing of features of either type can be characterised by simple arithmetic on distances from norm in units of the HDD. How the brain or the language relates ideas to sensations is a totally separate issue from how the mind does the trick. Normed discrimination theory addresses such issues by specifying what brain imaging or linguistic analysis needs to explain in psychological performance and phenomenology, as in examples below.

Finally at this point it should be noted that discrimination is the logical inverse of causation. The discriminating between stimulus levels achieved by a response is the same as that stimulus influencing the response levels. The half-discriminated levels of the stimulus are those which are equally likely to cause a particular size of response. Hence the measurement of a normed discriminal process is also the characterisastion of a causal mechanism that is currently operative in the mind of the participant. Wider implications of this equivalence are considered briefly at the end of this review.

Determinate mathematics

Interactions between input/output functions are represented by algebraic operations on the observed positions of test samples on dimensions in HDDs from norm, without any loose parameters. The only probabilistic calculation is simple regression, and its exact arithmetic is used to measure causal strength, not statistical effect size. First, the norm and HDD for each function is estimated by least-squares fit to a vertical section through the multidimensional 'cone' (hypercone) formed by the response to two (or more) stimulus features. The height of the fitted peak estimates any defect in the context relative to the unvarying aspects of the norm (Figure 2). Secondly, each hypothesised model of the interactions among discriminal processes is tested as the sole predictor in a linear regression onto the judgment to be explained (Figure 3).

Figures 2 and 3 here

The most realistic among the interactions calculated is the model with output values for the tested samples that best predict the quantitative judgments made. Experience so far is that, when the test samples are modest in number and kept tolerably close to the individual's norm, the best model usually accounts for over 80% of the variance in judgments, and often 95-99%. However, if a participant is given some samples very far from a norm, it is much more difficult to maintain a single strategy of judgments throughout the session. Then the variance accounted for at best may be about 50-70%, or even sometimes around 30%. The examples below illustrate this and other principles of the practice of normed multiple discrimination analysis.

Types of perceptual process

The verbal quantitative judgment to be explained may be analytic -- that is, specific to a particular stimulus. An analytical judgment may be driven solely by the specific source of stimulation, even when other cues are available. However, with a multifeatured task in a naturalistic context, the specificity and precision of a quantitative judgment may be informed by that affordance in some subtler way. For example, the redness of an apple may be judged better than that of a rubber ball covered with exactly the same distribution of reflectance, without any input from other senses.

Alternatively, a judgment may be integrative, informed by two or more features of the situation. Concrete actions, like pressing a button or selecting an object, are often integrative of all processed features, in or out of attention. Whatever number of affordances inform the judgments, normed discrimination treats the task as a comparison of the levels of the features of each test presentation with the levels in the norm used by the participant.

Integrative judgments often include conceptual features of the object or its context. The concept(s) may be implicit if the focus is on sensory features. On the other hand, explicitly conceptual evaluation may relegate sensed material characteristics to the periphery of attention. Which was happening is calculated from the data by normed discrimination scaling.

One possibility is that the material or symbolic stimuli in the environment control the perceptual judgment directly, without more complex transformations of the incoming pattern of information into the outgoing information (Booth & Freeman, 1993). This is in effect an overt mental process. Its calculation can be called a stimulatory model of the judgment.

The verbal concept used in an analytical judgment may serve as one of the inputs to an integrative judgment (Booth & Freeman, 1993). That concept may also be applied to another response's concept, as in deduction or some other reasoning process from one idea to another. That step between two concepts may have an effect on the integrative judgment. For example, the concept of a 'red' colour may call to mind the concept 'green' or 'yellow,' especially if the ripeness of an apple is being judged. Such conceptual or reasoning process models can account entirely for an integrative response such as familiarity or liking. There is then no empirical justification for the usual assumption that the judgment was decided on the basis of sensory processing, such as a dependence of a judgment of yellowness on stimulation of the retina by light of wavelength around 580 nm or a matching mixture of wavelengths. It may be easier to rate complex colour patterns (e.g., containing some red and some green) on a single concept related to ripeness, especially if there is no yellow on the apple.

A successfully analytical judgment applies the culturally appropriate verbal concept to an affording material or symbolic stimulus, e.g. warmth to felt infra-red radiation from the sun, or price to the monetary value seen alongside an item for sale. This application of a concept to a stimulus is the performance of a description (Booth & Freeman, 1993; Freeman & Booth, 2010). The estimated model of a descriptive process may account entirely for an integrative judgment. An example in words might be, “the sugar in that coffee has just the right sweetness for me.”

Still more complex interactions can be modelled from the data yielded by an individual participant's session on a type of object in a particular situation of its use. A response concept may be applied not only to another concept or to a source of stimulation but also to a description (a concept applied to a stimulus). If such conceptualisation of a description explains the variation in a judgment better than any other model, that is evidence that those decisions have considerable depth of meaning. If similarity to an emotionally significant object is being rated (or rapidly reacted to), such as a facial expression or a favourite food, that conceptualisation of a description could be the affect evoked. For example, judging a person to be welcoming might be explained best by attributing friendliness to visibly upturned corners of the lips that are conceived to express happiness. If a disposition to act is rated, such as readiness to buy an item, conceiving the expensiveness of the price as value for money could reflect the intention of the purchase.

The remaining type of process that is modelled in the current development of normed discrimination theory is applying a description to a stimulatory process. For example, the aroma of an overripe apple might be described as banana-sweet. Giving a stimulatory process a conceptualisation in terms of a stimulus is a minimal model of having a percept, in the sense of a consciously recognised feature. A visual example might be motion that is described as dangerously fast. Some percepts have the phenomenology of embodiment that characterises a sensation, in the ordinary sense of that word (Booth, 2007). Light as bright as an approaching headlight at nighttime can be dazzling. A sound may be loud enough to be uncomfortable. Specifically noticed touches, tastes and smells are percepts that are bodily enough to be sensations. Percepts of stimulation from within the body (the internal environment) are paradigmatic sensations, such as a pain in the back or fullness after a meal.

In contrast to a perceptual process, a stimulatory process that is neither described (a perceptual process) nor conceptualised (a descriptive process) may make a subconscious contribution to an integrative judgment. The first experimental result to be reviewed illustrates this distinction.

Discrimination without description of differences

In an experiment on a single discrimination within a familiar context, gustatory stimulation by varied concentrations of caffeine in a participant's usual drink of coffee affected ratings of preference more than ratings of bitterness in about half the people tested (Booth, Conner & Gibson, 1989). Presumably the bitter (and sour) compounds in roast coffee beans have tastes that are liable to mask the taste of caffeine. Since there are genetic variations in sensitivity of receptors for bitter-tasting compounds, the contribution of caffeine to the overall taste could affect behavioural disposition without the analytical concept being usable, even after it was brought to attention by a request to rate how “bitter” each coffee was.

The discrimination tests were conducted naturalistically by making each sample in full view of the participant so that it looked identical to the usual coffee consumed at that time of day with or without milk and/or sugar (Booth *et al*., 1989; Booth, Sharpe & Conner, 2011). In the first round of testing, the participants were asked simply how much they liked each “brand,” with no mention of the strength or taste of the coffees. That is, the visual context was held constant both materially and socially (or at worst it varied by small amounts in uncontrolled ways). The light reflected by the cream fat globules in milk may be more important in judgments of coffee strength than the masking of bitterness by the globules’ smoothness or by the casein or lactose also in milk (Richardson-Harman & Booth, 2006).

In a second round of tests, the sequence of caffeine levels was usually changed and ratings were added of the sample’s bitterness relative to the participant's usual coffee. Interpolation of the function of bitterness on the logarithm of caffeine concentration gave the individual’s norm point for caffeine by taste.

The initial normed discrimination analysis of single sensory features using both analytical concepts and integrative preferences (Booth *et al*., 1983; Conner *et al*., 1988b) was later developed to address multiple sensory and conceptual features (Booth & Freeman, 1993). Conceptual and descriptive models were added to the Booth-Conner stimulatory models. Hence it became feasible to use degree of preference to measure discrimination between intensities of bitterness as well as between levels of stimulation by caffeine, i.e. to diagnose conceptual processing within the integration of the taste of caffeine into the coffee drinking context. Subsequently, three more models were added to the Booth-Freeman-Conner theory (reasoning, meaning and percept) and a fully algorithmic tool was programmed (Booth *et al*., 2008; Galea, Chechlacz, Booth *et al*., 2008). This enabled full-scale reanalysis of the data on effects of the taste of caffeine on coffee preference and bitterness in accord with the mature Booth-Sharpe-Freeman-Conner theory of normed multiple discriminations (Booth *et al*., 2011).

The earlier conclusion was confirmed: more than half the panel discriminated levels of caffeine worse by how bitter the coffee was (on the second run through the samples) than by how likely they were to choose the coffee, either before or after mention of the word “bitter” (34 and 28 out of 52). Normed discrimination scaling showed whether and how the concept of bitterness had been used implicitly before the term had been voiced. Most of the participants whose preferences were more discriminating than their intensities on the second run (19 out of the 28) implicitly conceptualised the coffee as bitter during the first run. Six others used the concept descriptively and one applied the description of caffeine as bitter to the stimulation from caffeine (a perceptual process or sensation of bitter taste). Only the two remaining participants had preference judgments controlled by a purely stimulatory process from caffeine. Since use of the concept to discriminate was not implicated in the differential acuity of their preferences, these are the only panellists to whom the differences in stimulation from caffeine could have been subconscious. Multiple discrimination modelling was essential to distinguish implicit awareness of the taste of caffeine from a genuinely subconscious discrimination of differences (Booth *et al*., 2011).

Separate versus shared dimensions

Many perceptible sources of stimulation to the senses (affordances) have nothing in common with each other, within or across modalities. The default hypothesis is that the information from each source is processed separately from information from the other source(s). That is, the stimulus features of the psychophysical functions are on orthogonal dimensions. In other words, the discriminal processes operate over distinct transmission channels until the signals are integrated into the interaction that immediately controls a judgment. Hence, in the model of that interactive influence within normed discrimination theory, the distance of each feature from the norm is squared and the square root is taken of the sum of those squares to give a single multidimensional distance (Booth & Freeman, 1993). Since Pythagoras's theorem generalises over an unlimited number of dimensions, any number of input categories can be included in that model of separate processes.

In some cases, however, two physically or conceptually separable affordances might be processed as also having an aspect in common. For this to happen all the way from stimulation to response, the two sources would have to act in part on a single type of receptor. In norm-zeroed multidimensional modelling of such interactions among discriminal processes, the two distances perceived in each test stimulus add together (Booth & Freeman, 1993). Note that either distance may be above the norm (having a positive sign) or below it (negatively signed). In signal transmission theory, such features are processed over the same channel and their strengths summate.

Behavioural identification of receptors

This distinction between rectangular and summative interactions is a key algorithm in normed multiple discrimination analysis. Addition of distances was first tested against orthogonality using two sugars and two acids found in fruit (Booth & Freeman, 1993; Freeman, 1996; Freeman & Booth, 1997). The evidence was that HDDs from norm added for the sugars and for the acids but usually combined orthogonally between sugars and acids. At around that time, the related idea of unidimensionality of coding was transferred from colour vision (Pugh, 1988) to pairs of sugars in a mathematically complex approach based on signal detection (Breslin, Beauchamp & Pugh 1996; Breslin, Kemp & Beauchamp, 1994). Neither group's data showed discrimination between sucrose, fructose and glucose at sweetness-matched concentrations in the low to moderate range. Higher ranges of concentration differ in viscosity at equal intensities of sweetness. In addition, equally sweet concentrations of a monosaccharide and a disaccharide differ in osmotic strength, sensed as a difference in tang (rasp) between the test solutions. Because of these confounding sensory factors, the method of seeking concentrations at which pairs of sugars are indiscriminable is much more limited than normed multiple discrimination for identifying actions on a single receptor (i.e. unidimensional coding) to which an integrative judgment gives access.

The general problem: profiles of receptors stimulated

Those hexoses and their disaccharides are exceptional. Very few tastants or odourants have a pair of concentrations at which they are indiscriminable. This principle has long been implicitly acknowledged for chemical compounds that stimulate olfactory receptors (Polak, 1973). The same idea of each compound stimulating a distinct profile of receptor types is implied for gustation by evidence that multiple receptors activate each afferent associated with a taste pore (Roper, 2007). Extension of classic theory of the processing of artificially isolated signals to multiple detection or discrimination is complex at best and may be mechanistically questionable (Macmillan & Creelman, 2004). An immediate and economical solution is provided by normed multiple discrimination within well learned contexts (Booth & Freeman, 1993).

A pair of affordances (A and B) can share a perceived aspect and each have an aspect which is distinct from the other affordance. Such a case is represented by a three-dimensional model, (A + B) ¬ A ¬ B, where the right-angled keyboard character means the summing of squared discrimination distances from norm of the elements on either side of the symbol, and then the square root being taken of the sum of all the squares in the formula (sqrtSoS).

The three elements can be represented on a graph with three axes, e.g. x for A, y for B and z for A + B (although this leaves no visualisable axis for the modelled response). It may be easier to see the elements as signal-transmitting channels by use of a Venn diagram (Figure 4). Each bounded area can be interpreted as the cross-section of a pipe transferring information from input on the reader's side towards a shared output behind the plane of the diagram. Two overlapping areas (A and B) represent the above 3D model. If Venn area B is entirely within area A, then the multiple discrimination model of the interactive influence on the judgment is A ¬ (A + B). In that case, there are just two dimensions, one simple (A) and the other complex (A + B).

Figure 4 here

Tastants A and B might be two amino acids, each tasting sweet (A + B), but one could also taste sour (A) and the other bitter (B). The distinctions between the shared channel (A + B) and the two separate channels (A ¬ B) can be tested fiercely with tertiary and quaternary mixtures, if assessors have a norm from familiarity with a material tasting sweet, sour and bitter (such as coffee with sugar, or soy sauce on a bland food). If C is a fruit acid and D a widely used bitter compound (such as caffeine) and the best model of mixtures with the two amino acids was (A + B) ¬ (A + C) ¬ (B + D), that would strongly support the existence of a single channel for part of signal from A and part of B's signal alongside another signal from each amino acid on the same channel as that sour compound or that bitter compound. That is, multiple unidimensionalities are identifiable (Booth, 2008; Booth *et al*., 2008; Freeman, Richardson, Kendal-Reed & Booth, 1993).

That is good news for multisensory perception because chemical and mechanical stimuli differ from colour in having multiple independently varying physical parameters. Light only has wavelength (perfectly confounded with frequency). Chemical compounds have complicated shapes and charges on their electronic envelope through which they interact with receptors. Furthermore, both ligand and binding site change shape as they interact.

Hence quantitative structure-activity research has serious difficulties. The dynamics of tactile stimulation of skin are at least as complex at the micrometre scale (Booth, 2005).

Several types of single-channel processing of a visual feature and a feature in another sensory modality are under investigation currently. Ernst and Banks (2002) have used the variance component of the JND / HDD (without the slope) to analyse such interaction between sight and touch. The food research community has long been aware that sight of the colour of a fruit affects recognition of its aroma. A pear-flavoured drink coloured strawberry red may 'taste' like strawberry. However such demonstrations do not provide quantitative data on relationships between responses and stimuli. The existing evidence has been critically reviewed (Levitan, Carmel, Zampini *et al*., 2008). Clearly these phenomena are amenable to normed discrimination analysis. The effects might all arise from an implicit multi-featured norm that is activated by the name of a source of colour and aroma. A similar suggestion has been made for aroma by itself (Stevenson & Boakes, 2003), since each compound in a natural mixture of volatiles stimulates its own profile of receptors (Polak, 1973).

The most widely known case of integration across the senses in food and drink is flavour from taste and odour. Associative conditioning can be involved, as has been shown for sweetness and attractiveness of an aroma (Stevenson, Boakes & Prescott, 1998; Yeomans, Mobini, Elliman *et al*., 2006). It remains to be clarified if the sweetness conditions the aroma (CS-US association), or as well or instead configures with it (CS1 + CS2 association). Multiple discrimination theory distinguishes between two criteria for any such configural conditioning. Creation of a third stimulus by reinforcing a conjunction of two stimuli would be a unidimensional interaction. In contrast, accounts of configural stimuli that treat them as compounds of the two stimuli may be modelled best as two-dimensional.

Synaesthesias also need investigating in normed multiple-discrimination designs, applying interference paradigms like those used to identify the visuospatial scratchpad and phonological loop in working memory.

Sensory and conceptual submodalities of sight

The first application of normed discrimination theory to symbolic affordances used vision to deliver that conceptual information, while gustation provided an example of sensory information (Freeman, 1996; Freeman & Booth, 2010). A majority of participants distinguished between the symbolic dimension of written words that conveyed a concept of dietary calories and the material dimension of gustatory stimulation from sugar. Remarkably, some participants used the same channel for the sweetener sensed via the tongue and the viewed meaning of a label stating the calories in the sweetener of a drink.The influence of these unidimensionally processing participants can be seen in the shape of the surface formed by accumulating the individuals' norm ranges. (The 'norm range' is one HDD on either side of the norm, in this case the individual's most preferred combination of calories and sweetness -- the ideal point). Single-channel processing creates a diagonal stripe across the contour map, whereas two-channel processing contributes an oval (Fig. 5).

Figure 5 here

The second experiment to span sensory and conceptual stimuli was purely visual, again using the personal ideal as the norm. The participants viewed both the amount of spread on a standard-sized piece of bread (visible as thickness) and the spread's percentage content of fat written alongside (Freeman, 1996). One of the most prevalent two models of the perceptions driving preferences was two-dimensional but the other was one-dimensional (2D and 1D in Fig. 6). In the 2D integrations, it was most often the participant's concept of the read fat content of the spread that was distinct from her or his concept of the amount sensed visually (Fig. 6: CON-2D-CON). In the 1D processing, however, that concept for viewed amount was processed on the same dimension as the description of read fat content by its concept (Fig. 6: DESC-1D-CON).

Figure 6 here

The above cases are all evidence that sight of a food contributes to an appetite for it. Just seeing a food can elicit a craving for it. Indeed, craving a seen foodstuff makes substantial demands on visual processing: less craving is expressed if visual working memory is loaded with another task (Kemps & Tiggemann, 2010). It remains to be seen how much of that distraction is sensory and how much conceptual.

Cravings can occur also without sight (or smell) of food. Thinking of the food or reading or speaking its name is sufficient. Hence, descriptions of familiar food items can be used to construct a multi-psychophysical design. In a pilot experiment, vignettes of eight food items varied independently the described size of the portion, whether it had real chocolate in it or only chocolate flavouring, how sweet it was stated to be, and whether or not the item contained vitamins. After reading each description, the participant rated strength of craving and how chocolatey, sweet, filling and comforting the described item would be to eat. The most successful model from normed discrimination scaling of the data from one participant is shown in Figure 7.

Figure 7 here

The operation of vision's symbolic submodality on these stimuli to induce craving in this individual involved two complex sets of described stimulatory processes -- maybe sensations or imagery. The slightly more influential percept was a commonality of a comforting amount of food ascribed to the sugar in the food (represented on the abscissa of Figure 7 by the formula S2//S3/R5 within the model, accounting for 30% of the variance), with the comfort of sugar felt to be in the amount of the food (S3//S2/R5) and comfort in amount when the food was read to contain vitamins (S4//S3/R5). The other percept was a feature in common among the same three symbolic sources of visual stimulation with similar relative amounts of influence. The description of the sugar, however, was that it made the vitamins chocolatey (S2//S4/R2) -- perhaps a feeling that 'the medicine pill was sugared' with chocolate. The stated amount of food was craved when it had comfortingly real chocolate in it (S3//S1/R5). The described vitamin content contributed to the craving in this same somewhat less influential way when in a large amount of sweet food (S4//S3/R3).

It follows that even words can be sensed as well as conceptualised (presumably whether seen in writing or heard in speech). That is to say, whether any manipulation is viewed materially or symbolically can be an option for the perceiver. Pictures are often used in brain imaging of appetite for food (reviewed by Chechlacz, Rotshstein, Klamer *et al*., 2009). Yet no psychophysics has been done on the pictures or the pictured foods. The foods viewed in fMRI by Chechlacz *et al*. (2009) were varied in strengths of three features. So it was possible the measure the effects of those features on appetite for the pictured foods (Galea *et al*., 2008). Normed discrimination could then determine whether these features of the pictured foods were perceived sensorially or conceptually.

Each participant was shown the same set of 36 photographs of foods. Therefore their features were unlikely to have been well balanced around the personal norm for everyone. Some foods may have been disliked by some assessors. Also, if some feature levels were generally far from the norm, then other features with strengths spanning the norm could not generate a maximum response. Hence there was liable to be a large contextual defect (Booth & Freeman, 1993). The peaks of the conic sections observed were indeed held far below the norm response (e.g., Fig. 8).

Figure 8 here

Hence the participants' norms for appetising food could not be consistent across the set of pictures. The best normed discrimination model sometimes accounted for only a low proportion of the variance in the ratings of appetite for each pictured food item. One of the highest values for r^2 was 61%. That model is used here to illustrate. It was descriptive, in two dimensions, i.e. two independent signals were identified as influences on appetite. The descriptive elements in each dimension used the concept of the pleasantness of the pictured object, whether that object was a food or a similarly shaped and coloured non-food that was used as control for purely visual appeal.

The signal with greater influence on appetite had two descriptive elements -- that is, they had a feature in common. The similarity represented by this dimension was in the pleasant aspects of non-food objects that corresponded in size to the food portion and other pleasant aspects in parallel to variation in fat content. It seems that the eye-appeal of big, glossy objects had most influence on this participant's appetite for the foods.

The separate, smaller influence on appetite was the pleasantness of the foods with higher sugar content. Further data would be needed to distinguish between expectation of sweetness and of other effects of sugar, such as rapid suppression of appetite.

This participant was in his 30s, with average dietary psychology scores, except for having next to the highest score for confidence in self-control of his diet. He was seriously obese (BMI = 38 $kg.m^{-1}$) and had type 2 diabetes mellitus. It is easy to gain the impression of someone who loves eating and is not disposed to cut back on his large portions of fatty foods despite the diabetes and obesity.

Four odourants in visual context

The next illustration is from an early use of normed discrimination, involving only stimulatory, conceptual and descriptive models. The varied features were purely olfactory but the context was visual, with sight both of the food and its name - a strawberry (Booth *et al*., 1985; Booth, Kendal-Reed & Freeman, 2010). The data shown here come from a participant who had four sessions on the mixtures of four odourants that in the right balance produced a realistic strawberry aroma (Fig. 9).

Figure 9 here

From the start, the verbal concepts specific to each of the four odourants dominated judgments of overall similarity, operating over four separate dimensions (4-d in Fig. 9, top left-hand panel). Such 4-d conceptual processing accounted for virtually all the variance in the fourth session. Nevertheless most other tested processes were also operative during the first session. In all three sorts of processing calculated, the initial impression appears to have been that the four odourants all smelt the same in part (1-d), while also being distinct (4-d).

Subsequent sessions saw 4-d processing come to predominate in both strength and balance, and conceptually too as in the overall judgments, with some hint of descriptive processing (Fig 9, lower panels). That is, this participant learnt to use the concepts that related to the odourants, rather than following their stimulation directly.

The participants were also asked to assess the strength of the aroma separately from the realism of its quality or balance. These aspects of overall distance from norm have different mathematical models (Booth & Freeman, 1993). Interestingly, judgments of quality paralleled the 4-d processing in overall similarity to strawberry aroma, while the intensity ratings accounted for the unidimensional integration. However, the 4-d quality judgments were descriptive, rather than conceptual or stimulatory as the overall judgments were. Perhaps the task of judging the balance among odour notes draws on previously developed skills of applying culturally agreed concepts to patterns of sensory stimulation (Booth, 1995).

Four fracture parameters in visual context

An intermediate development of normed discrimination was also limited to four dimensions but including reasoning processes (concept on concept) as well as conceptual, stimulatory and descriptive mediation of the influences of material features on integrative verbal judgments. This modelling has been applied to the crackling that is heard and felt during the first bites into a biscuit by the incisor teeth and/or premolars and then the molars.

The detailed psychophysics can be found in the full publication (Mobini, Platts & Booth, 2011). Of most relevance here is another example of changes in perceptual processing when the samples are presented again after somewhat more analytical concepts have been named in addition to the globally integrative concept of the norm (Fig. 10).

Figure 10 here

The highest proportion of the participants used stimulatory processing in their first run-through biting the test biscuits. There were however large minorities using either conceptual processing or reasoning from concept to concept. That is, the concepts implicit in the participant’s initial overall judgments were similar to the consensual terms introduced after that run. After the participants began analytical assessments, as well as judging overall similarity to the usual biscuit, there was a shift to more of the panel using the concepts to describe the stimulation. In quantitative descriptive analysis, panellists are trained in use of a vocabulary to describe features in exemplars. From these findings of ours, it seems that experience in everyday life of the situations like the laboratory test is sufficient to enable effective use of the relationship of familiar words to the features that were attended to from the start.

Wider implications

Psychophysical approaches to cognition have seldom had a foundation in discriminative performance, or detection (Algom, 1992). With the advent of human brain imaging, there is a pressing question of how a person's networks of mental causation are implemented in neural processing within the material universe of bodily sensing and movement in the biosphere. With the more recent 'cultural turn' in psychology, some attention is now also being paid to the equally unsolved issue of how the mental system has been inculcated by interpersonal processing within the social universe of symbolic representations such as languages. Neither enterprise can succeed without a fundamental science of the mechanisms of the mind. Not only is this psychological causation what needs to be explained by neurophysiology and cultural analysis respectively. Also these mental networks develop by lifelong interactions between genomic expression and societal education and so their measurement is needed for advance in the science of individual development.

These may be regarded by some as wearisome truisms. Yet they are denied by neural reductionists on one side and by social constructionists on the other. Therefore, to prevent misunderstanding, a position needs to be sketched on these distinct types of causal system, coordinated by development within a unitary personal reality.

The above position repudiates both environmentalist behaviourism and also phenomenological introspectionism. This is not a trivial matter, because both those traditions live on under the 'cognitivist' umbrella. For example, some psychophysicists remain content to relate the physical characteristics of stimuli to the times that subjects take to press a response button. The mediating processes invoked may also be physical, in photoreceptors for example, or dorsal and ventral pathways. Others retain Fechner's meaning for the term ‘psychophysics’ that he invented, and assume that verbal responses describe private contents of consciousness, rather than exercising a public competence at handling concepts. The opening of this paper characterised psychophysics in neither way. Rather**,** a psychophysical function was treated as one of an interacting set of mental processes, including some by which perception of a material affordance (source of physical stimulation, e.g. sugar) causes the imposition of meaning onto a linguistic affordance (an emitted verbal judgment, e.g. “sweet”). Furthermore, a linguistic affordance can give rise to perception of meaning which then causes intention giving rise to manipulation of a material affordance, e.g. selection of an item of food. A lot of experimental psychology has worked with reaction times to verbal stimuli. The evidence for mental causation has the same form.

Hence normed multidimensional discrimination provides multisensorial perception with a key role in a much larger enterprise. It offers tools for building an explanatory bridge between the ongoing contexts of human performance and phenomenology and its biological and social origins. A mind is 'grounded' in the physical system of a brain and body and in the social system of a culture and language. Embodiment and acculturation begin in the early development of the individual and continue throughout life. The links between a person's mind and brain, or mind and culture, are not mysterious further sorts of upward or downward causation. Cause-effect mechanisms are within the mind, within the material world or within the social world, not between them. During perception and action, the causal networking already built within the mind extracts and imposes information. We can investigate the conscious and unconscious causal processing networks within minds in their current state of development. The roles of brain imaging or cultural analysis are not to make the investigation of cognitive interactions redundant but to test between rival hypotheses that are beyond normed discrimination alone and no other purely psychological investigation has so far been able to resolve.

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[No Tables]

Captions to Figures

Figure 1. Equal differences are equally discriminated in symbolic stimuli. Notional data for rated intensities of sweet and orangey tastes against sweetener ratios, in a drink with an orange colour and aroma, and fruit acid as well as sugar.

Figure 2. A normed psychophysical function of judged likelihood of consuming ("always choose" to "never choose" and worse) a familiar orange-flavoured drink against concentration ratios of sucrose (left-hand panel) or of citric acid (right-hand panel). Broken line: best fitting vertical conic section (a right hyperbola). Continuous line: tangents (isosceles triangle) intersecting at the joint norm for sucrose and citric acid (this assessor's ideal point, scored as zero). Letters A to H: samples in sequence of testing (A first, H last). (Data from Figure 5.3 in Booth, 1994, collected for inclusion in Freeman, 1996).

Figure 3. Least-squares fit of values from the normed discrimination formula for a two-dimensional stimulatory model of rated disposition (R1) to choose the sample of the drink (from the data in Fig. 2). The regression line accounts for 79% of the variance in the integrative perceptual judgments. S2: citric acid, contributing 51% to the model. S1: sucrose, contributing 49%. ¬: square root of sum of squares of discrimination distances from norm

Figure 4. Cross-sections of 'pipes,' each transmitting a coherent set of informational patterns or codes. As usual in Venn diagrams, boundaries represent separate categories, such as A and B, plus a third stimulus (A + B) -- one criterion of a configurated conditioned stimulus.

Figure 5. Contour map of the number of individuals in a panel of N = 145 with an ideal area (one HDD on either side of the "always choose" point) at each coordinate, using each individual's best model of the sight of labelled sweetener calories, either "NutraSweet" (coded 0) or "sugar" (coded 1), and taste of sucrose (logarithm of molality). The ideal area is oval for a two-dimensional model and a diagonal stripe for a one-dimensional model. (From Freeman, 1996).

Figure 6. One- and two-dimensional integration of material and symbolic visual features into judgments of likelihood of eating a piece of bread with spread on it by young people who had expressed interest in reducing the amount of fat in their diet. Each column is the percentage

of participants who related the visible amount of the spread to the spread's content of fat displayed alongside the sample, in a manner diagnosed by normed multiple discrimination scaling in its initial form (Booth & Freeman, 1993). STIM: stimulatory process. DESC: descriptive process. CON: conceptual process. (After Freeman, 1996)

Figure 7. Processes by which an individual craved chocolatey foods on reading descriptions of them. Nearly all the variation in rated craving ($r^2 = 0.97$) was explained by two percepts (descriptions of stimulation), each extracting a common feature among three elements (that contributed the percentages given under the model on the horizontal axis). The descriptions were presented in the order 1st to 8th used as data points. For interpretation of this finding, see the text citing this Figure. S2: high versus low level of sugar. S3: size of item. S4: added vitamins or not. R1: "how much I crave it." R2: "chocolatey." R3: "sweet." R5: "comforting."

Figure 8. An individual's normed discrimination of a symbolic visual stimulus by an integrative judgment of attractiveness for eating (Galea *et al*., 2009; Chechlacz *et al*., 2009). Conic section through data for 36 three-featured objects -- photographs of foods varying almost independently in fat content, sugar content and amount pictured (visible volume). Continuous line: the hyperbolic function fitted to the raw data by least-squares regression. Broken line: the triangle bounding that hyperbola, with its apex at the norm response (extremely appetising, i.e. at the ideal point of the stimulus). Data points (numerals): code numbers for pictures of foods. (These data indicate that this person likes low-fat foods: ideal point around 5 g / 100 g.)

Figure 9. Variance accounted for in one participant's ratings of mixtures of four odourants over four sessions of the overall similarity to and strength and quality of strawberry aroma by stimulatory (S), conceptual (R) or descriptive (S/R) processes, either on separate dimensions (4-d) or on the same dimension (1-d). (See Booth, Kendal-Read & Freeman, 2010b.)

Figure 10. A shift from stimulatory (and conceptual or reasoning, R/R) to descriptive processing of the sound and/or feel of the crackling of a biscuit during the first two bites, when consensus verbal labels were introduced after the first run of the set of biscuit samples. (Redrawn from Mobini, Platts & Booth, 2011)

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Figure 1.

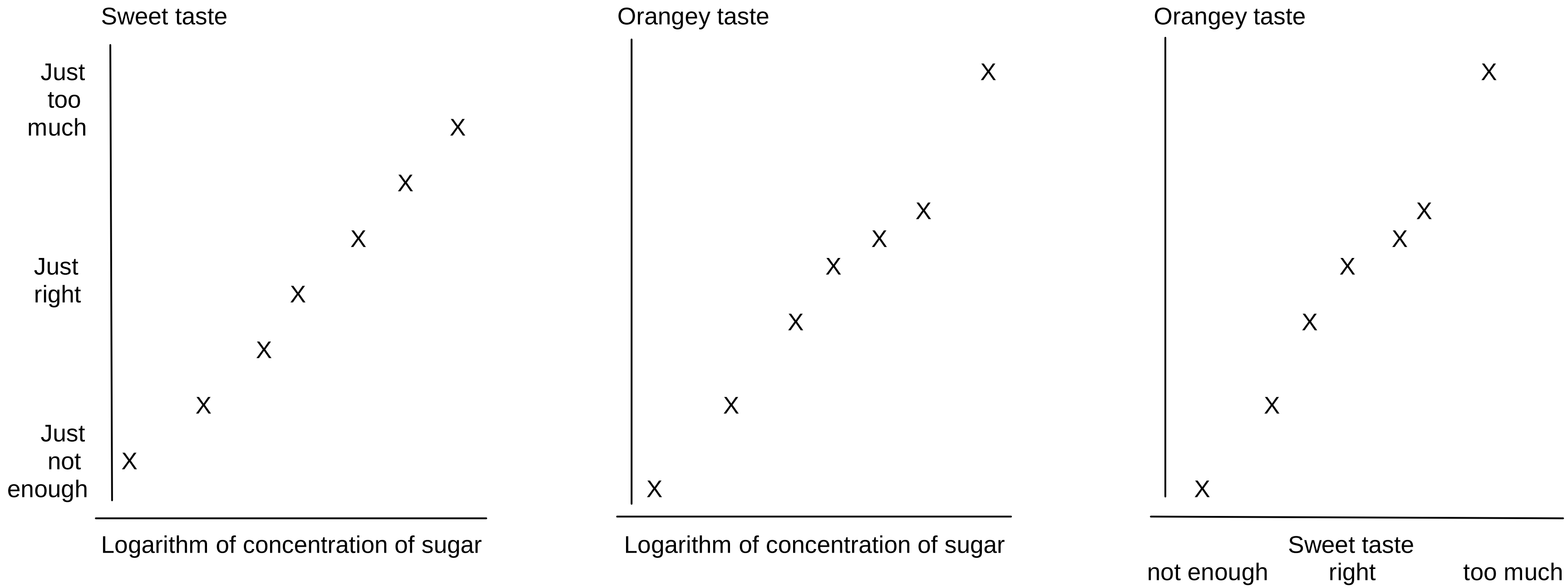

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Figure 2. *[Setter: the lines do <u>not</u> have to be coloured in a hard copy of the publication.]*

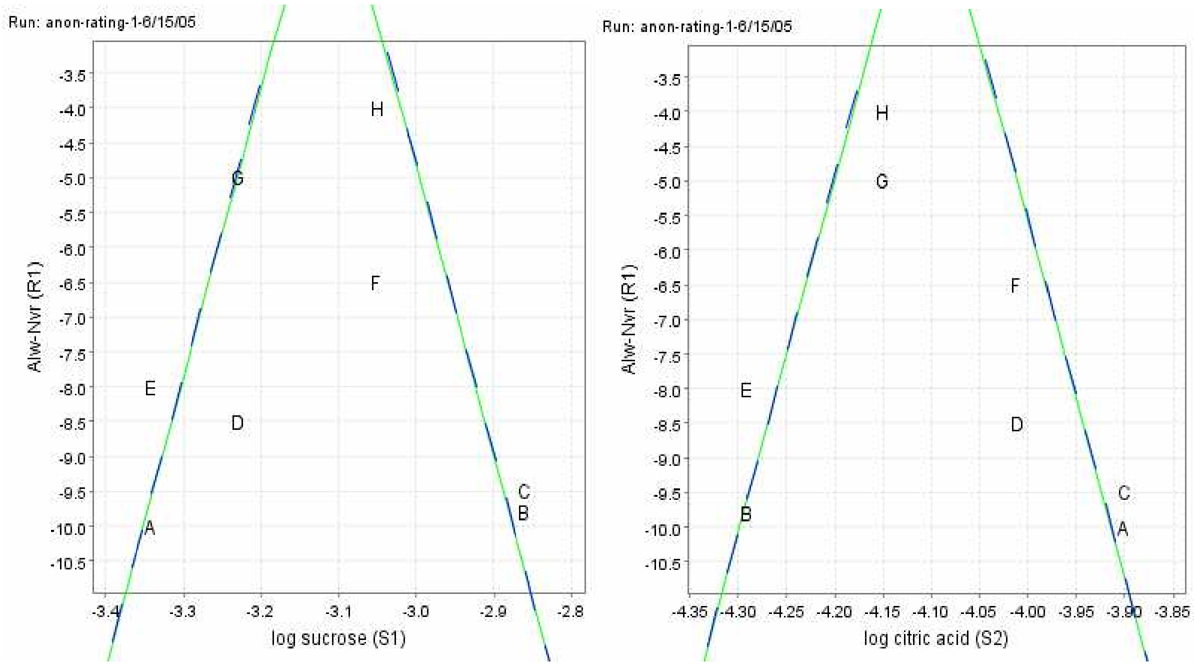
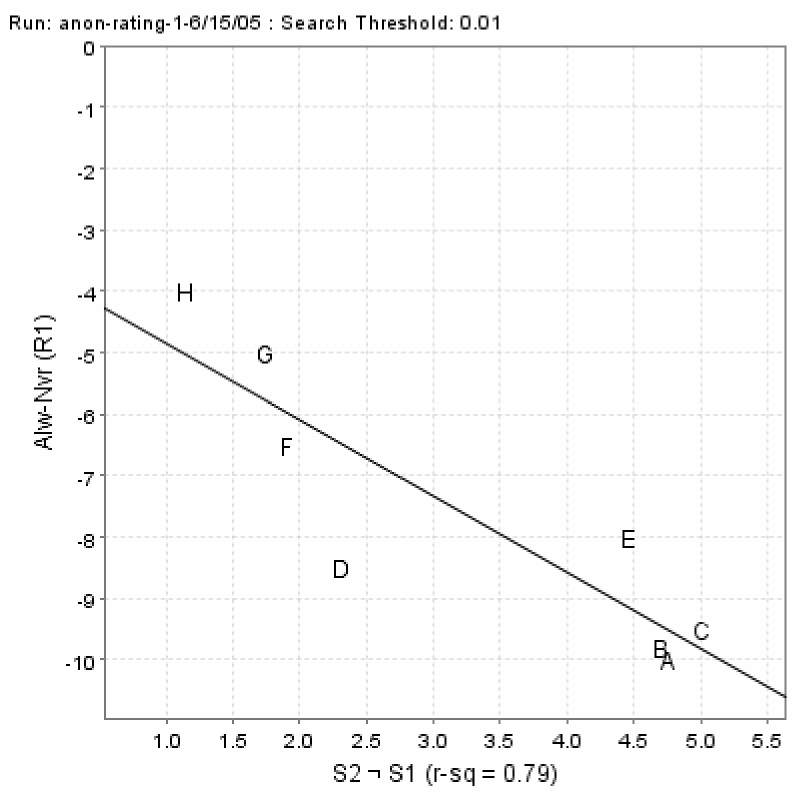


Figure 3.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Alw-Nvr (R1)
S2 ¬ S1 (r-sq = 0.79)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
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G
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A

Figure 4

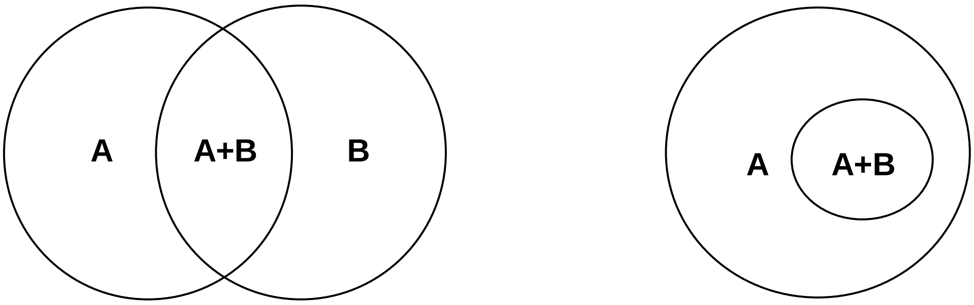

Figure 5.

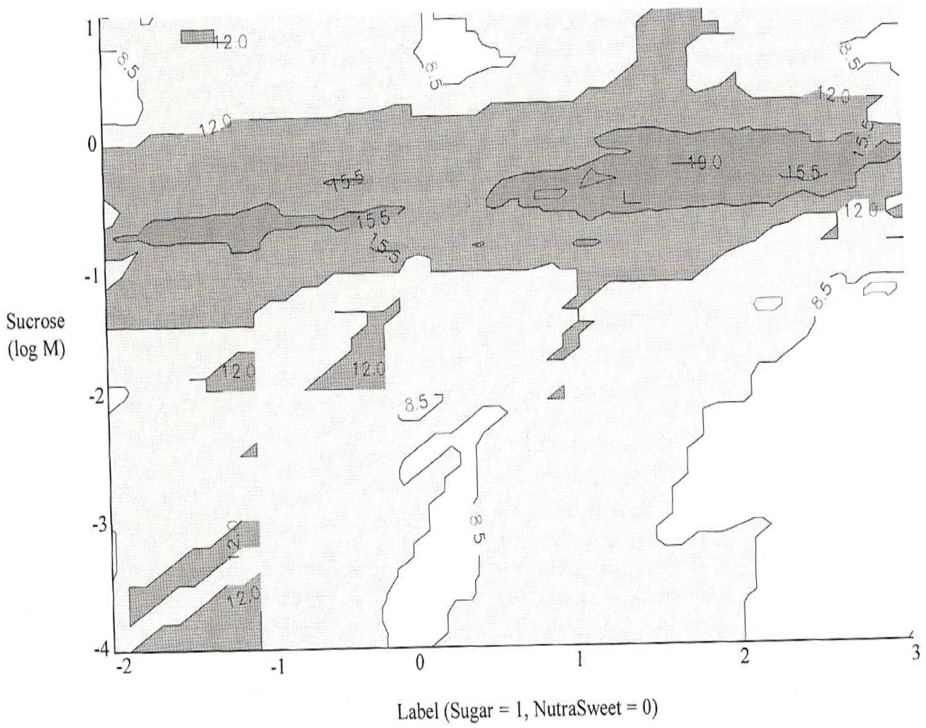

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Figure 6.

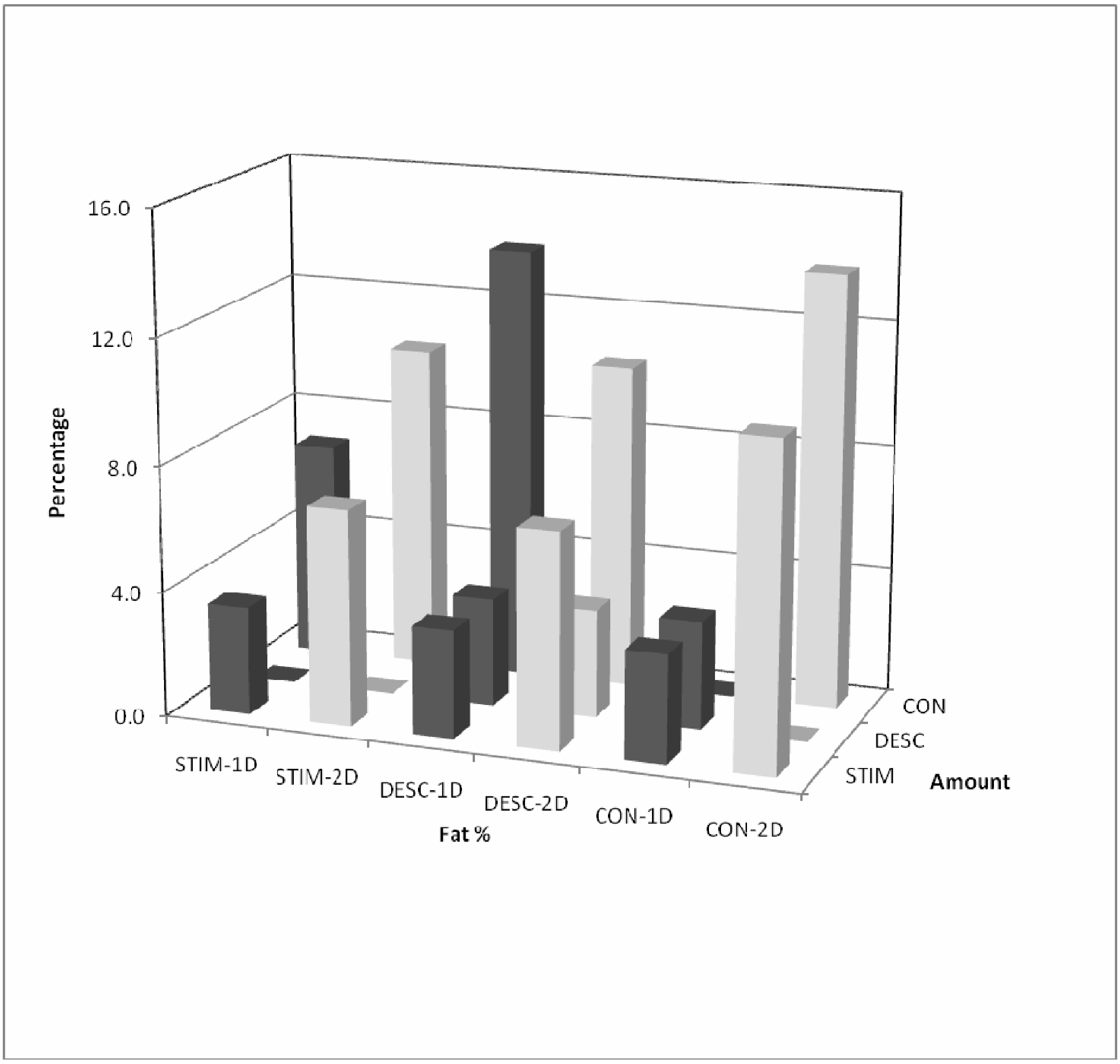
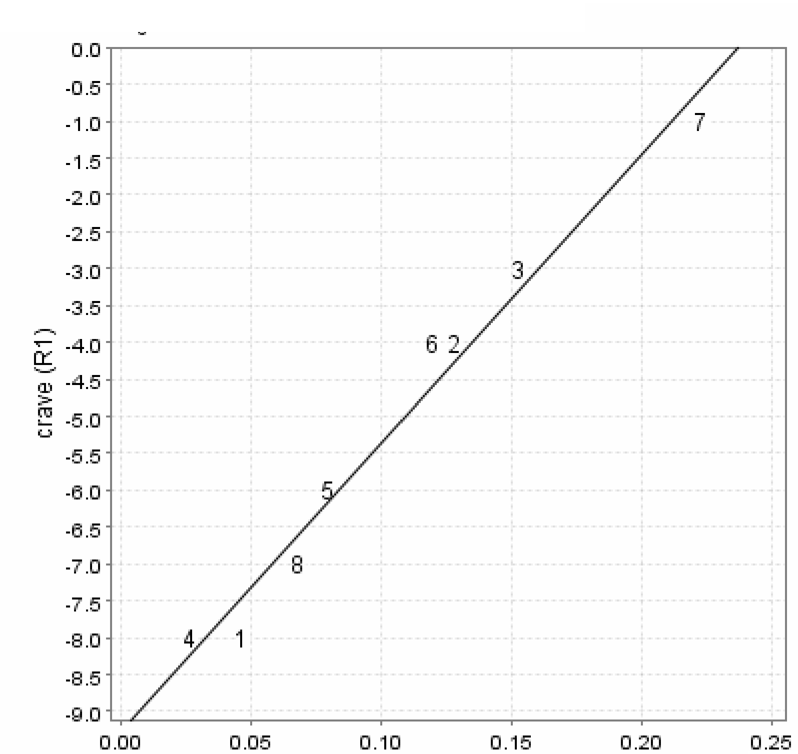

16.0
12.0
8.0
4.0
0.0
Percentage
STIM-1D
STIM-2D
DESC-1D
DESC-2D
CON-1D
CON-2D
Fat %
CON
DESC
STIM
Amount

Figure 7.



S2//S3/R5+S3//S2/R5+S4//S3/R5 ¬ S2//S4/R2+S3//S1/R5+S4//S3/R3 (r-sq=0.97)

30 12 9 25 11 9

Figure 8.

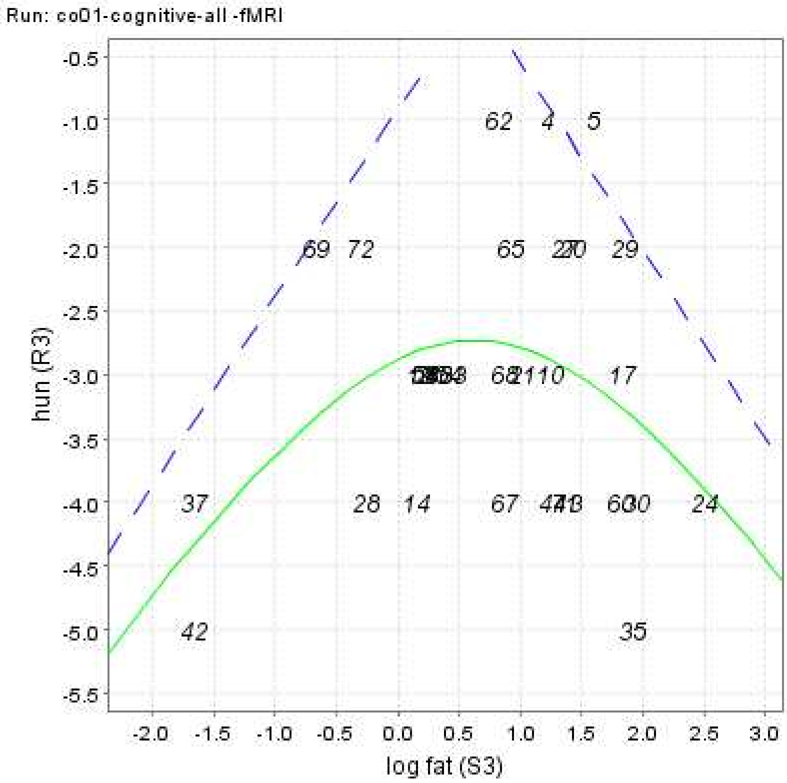


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Figure 9 *(split across two Landscape pages)*
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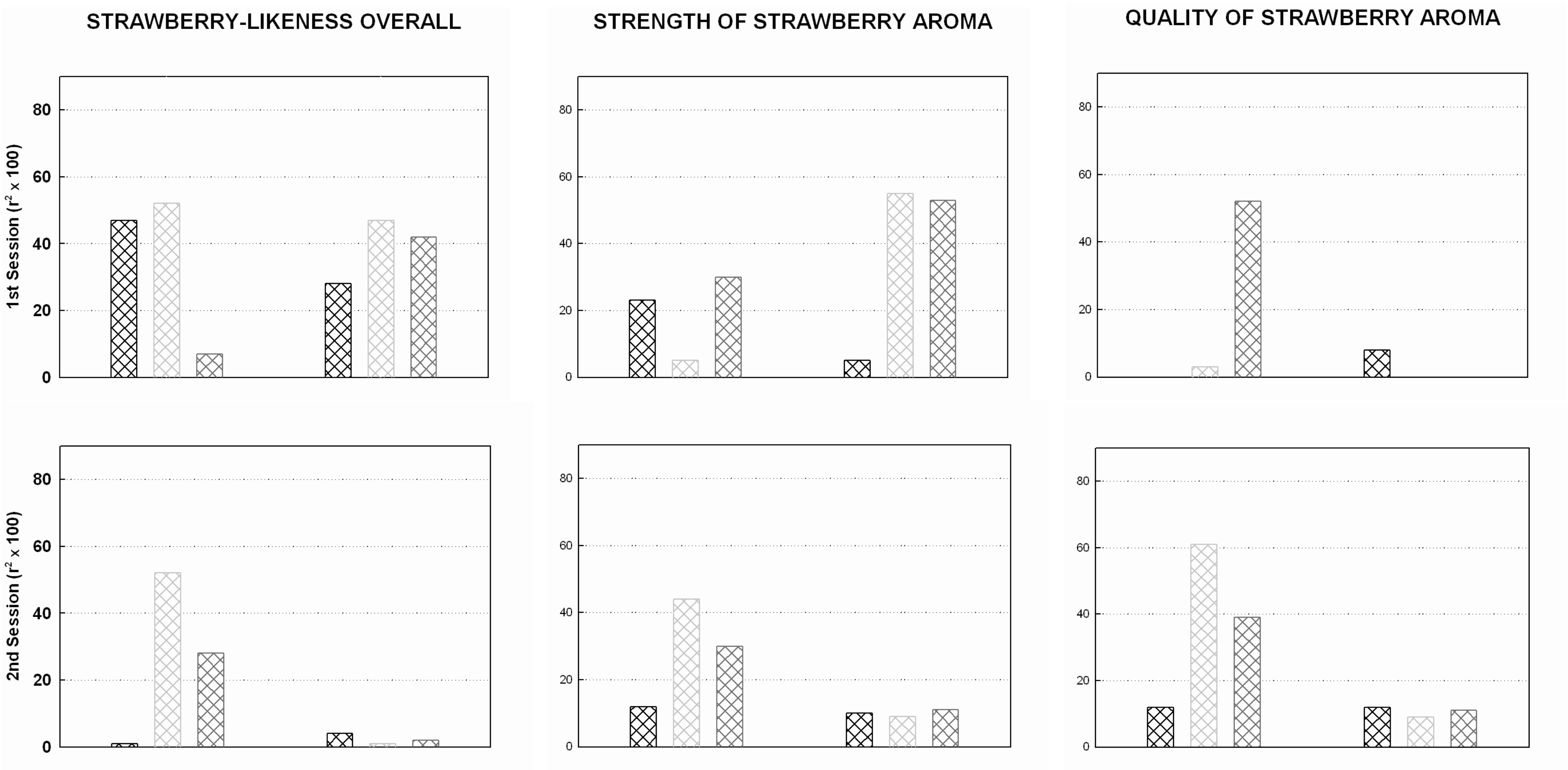

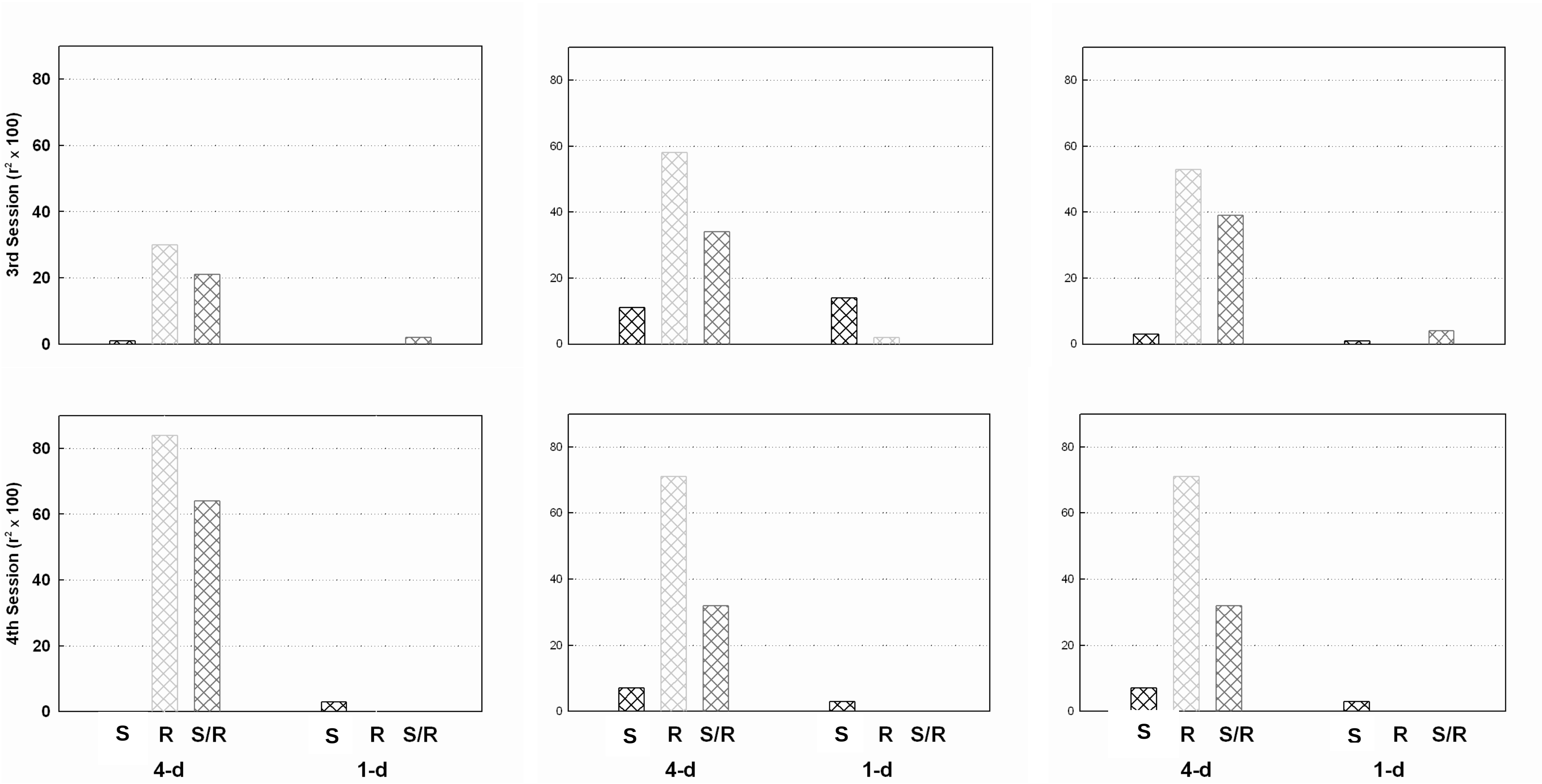

end of Figure 8

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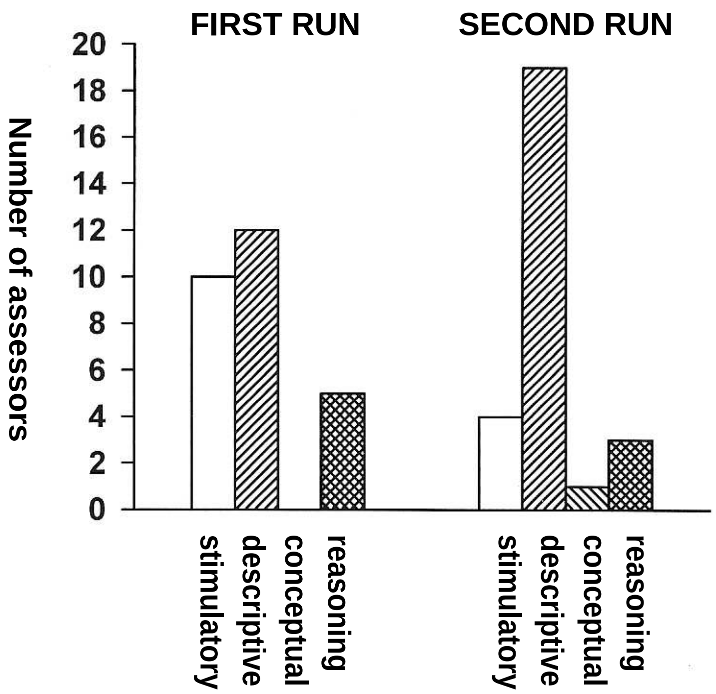
Figure 10


FIRST RUN
SECOND RUN
Number of assessors
20
18
16
14
12
10
8
6
4
2
0
stimulatory
descriptive
conceptual
reasoning
stimulatory
descriptive
conceptual
reasoning