A LONGITUDINAL STUDY OF CORTICAL EEG TO OLFACTORY STIMULATION, INVOLVING INTER- AND INTRA- SUBJECTIVE RESPONSES.

Suzanne Hotson, B.Sc (Hons)

Thesis submitted for the degree of Doctor of Philosophy

University of Warwick

Department of Psychology

March, 1993

Table of Contents

List of Tables, Figures and Plates

Appendices

Acknowledgements

I would like to thank and acknowledge the support and encouragement given to me by many people during the course of this thesis. First, to Dr. Steve Van Toller for providing the opportunity in the first place, and then for his advice and guidance. Thanks must also go to all those at Quest International, especially Dr. John Behan, for their financial support and encouragement. Thanks go especially to Dr. Martin Kendal-Reed for his continued calm advice and constant support. Certain Departmental lecturers also deserve special mention: Dr. Glyn Collis for his unbelievable patience and humour; Dr. Ian Morley for his continued good advice; and Dr. Gina Rippon for reminding me to "dot the eyes." Also in the Department I would like to thank Greg Milligan, for his continuing technical wizardry and willingness to offer support. Thanks are also in order for, Chris, Val, Lynda and Amanda for office support. Thanks also to David Sleight for his continued technical help during the three years.

Outside of the Psychology Department, I would like to thank Mike and Anne in the Photographic Department, not only for their technical abilities and willingness to help, but also for their humour. From the Department of Mathematics I would like to thank Dr. Mark Muldoon and Dr. Greg King, for their patience, advice and support. At Leeds University I would like to thank Dr. Arun Holden for his time and advice.

Thanks also to Laura, for her kindness, advice and confidence.

Finally, I offer my greatest thanks to Alex (artist and poet) and to Sibel (my mad Turkish friend) for their unfailing support, encouragement, patience and understanding. Thanks.

Above all I would like to dedicate this thesis to Mrs. W.M.Hartley, for always being there for me.

Declaration

The work contained in this thesis has been carried out entirely by the author. No material contained in this thesis has been used or submitted for any other purpose.

CHAPTER ONE

Why study olfaction ?

" Olfaction remains the simplest among sensory systems. For this reason, if for no other , the study of sensation and cognition might well begin with the sense of smell. But there are three other good reasons: the parallels that exist between olfaction and the other senses in their psychophysics, in the dynamics of the masses of neurons comprising them, and in the types of neural activity that they generate." (Freeman, 1985 19)

Evolutionary perspective

The first organisms to emerge on the planet survived because of their ability to sense the appropriate nutrients in their environment demonstrating that the chemical senses are our most primitive. The origin of the vertebrate olfactory system pre-dates the origin of the vertebrates themselves. This is evidenced by the fact that the most neurologically primitive vertebrates have a similar olfactory system to other vertebrates (Allison, 1953 cited by Masterton & Glendenning, 1978). Receptor types, ciliated receptor cells and glomeruli, across phyla arose early during evolution and provided the substrate for the development of further chemical sensing abilities in higher animals (Ache, 1991):

" If the olfactory system selectively recognises and processes some properties of the input signal rather than any others, if it selects particular aspects of the whole of available information, giving them special importance, it is because evolution has favoured these solutions among several others for their ecologic efficacy and has kept the appropriate neural organisation." (Holley, 1991: 330).

Present day relevance of odours

Further evidence that the olfactory sense is highly important to humans is the use of perfumes and incense. Since the beginning of recorded history people have used odours to perfume their world and it is difficult to appreciate the extent of their use in

Summary

This thesis forms the largest and most systematic study of the topographical EEG response to odour. The evolutionary history of the olfactory sense is briefly presented and its relevance to humans in the present day is considered. This thesis examines the information processing that occurs in this sensory system. The type of processing that the olfactory system utilises at each anatomical stage is discussed. The character of olfactory information that may reach neocortical levels in humans is considered in the light of the technology available to detect such information. The neurogenesis of the EEG is considered, together with questions concerning its postulated functional significance. The empirical work carried out uses the most advanced methodology for this type of study. The large number of odourants and subjects, combined with the longitudinal element, make this the most ambitious study of this nature undertaken. The issues surrounding the analysis and interpretation of EEG data are fully discussed and the impact of Chaos theory is considered. Five major analysis techniques were used on the data collected, but largely negative findings are reported. The reasons for the failure of this experimental paradigm are discussed and improvements are suggested for future work. The major contribution of this thesis lies in its exploration of the assumptions of the EEG response to odour. The thesis notes the lack of a conceptual framework that has hindered progress in the area of the "odour" EEG. Recent developments in neural network theory and Chaos theory are highlighted as possible alternative approaches to the modelling and understanding of the olfactory system.

civilisations such as the Egyptians, Greeks, Romans, Hebrews, Indians and Chinese. After the fall of Rome, the significant developments in the art of perfumery came with the Arabs and Persians who again delighted in their highly fragranced worlds. Many of these civilisations used odour not only for personal use but also for religious and ritual ceremonies (Stoddart, 1990).

The prevalence of odour is still with us today. The number and variety of perfumes available is astonishing. The therapeutic use of plants and plant oils also has many historical precedents and there has recently been an upsurge in interest in "aromatherapy." The point to notice for the purpose of this section however, is the need and desire of most people to surround themselves with odours for whatever reason.

Olfaction as a sensory system

Appendix 1 contains detailed information on the structure and function of the olfactory system, which can be read in conjunction with the following sections.

Properties of odour perception - What is to be coded ?

The olfactory system can be divided into different levels of processing: receptor neurons; olfactory glomeruli; mitral and tufted cells in the external plexiform layer; olfactory cortex; and the neocortex. Before considering the possible coding strategies employed at each stage of the olfactory system, it is important to be aware of what needs to be coded for the system to fulfil its purpose, and to solve its particular problems. For humans the conscious perceptions produced by the odour are of prime importance. The general properties of odour perception can be listed as: detection, magnitude estimation, quality discrimination, recognition and storage.

Globally, the olfactory system must also carry out some form of dynamic range compression as is the case in all other sensory systems. The number of olfactory receptors is very high but a few molecules are sufficient to reach a threshold level. Furthermore, identification of an odour can occur over several log. units of concentration.

Each glomerulus receives in the order of 10^4 receptor axons, but output from the olfactory bulb is much less.

The olfactory system must also solve the problem of generalization over equivalent receptors as no two odour inputs are likely to be the same, and often identification of an odour is accomplished with a pattern of input never previously encountered.

There is some evidence that some form of input selectivity occurs in the olfactory system. The receptor sheet responds to all inputs, but the olfactory bulb responds selectively. Freeman (1991a) suggests that this is evidence of continual modification of bulb sensitivity, by neural mechanisms of motivation, associative learning and habituation.

Recordings of neural activity from the bulb have demonstrated high levels of variability and randomness, which suggest that structures receiving output from the bulb must have some way of imposing order on the signals.

Finally, identification of stimuli (in rabbits) is extremely rapid often occurring in 200msec. Since the primary transduction process occurs within 100msec, this leaves 100msec for the bulb to detect and classify the odour. (Freeman 1991a). This indicates that stored data is in a highly compressed form.

One important fact to consider is that odour molecules have no spatial characteristics per se, and as a consequence the source of olfactory stimulation is not encoded by the spatial distribution of receptor activity in the epithelium. This leaves the spatial patterns of second and third order neurons free to code stimulus intensity or quality (Castellucci, 1985).

Spatial or temporal ? - Possible coding strategies

The various sensory systems have a significant number of common principles and deviations from the norm may disclose further principles. They share the same need to code stimulus characteristics such as quality and intensity, a common neural machinery for encoding, and potential neural codes. The requirement for any candidate code is that

it responds differentially to discriminably different stimuli. Spatial codes are those which use the parameter of 'which' neurons are responding. Labelled-line codes, which assume a separate kind of receptor cell for each stimulus, and across fibre pattern theory are both examples of spatial codes (Erikson & Schiffman, 1975 cited by Erikson 1978). The difference with the across fibre theory is that the quality of the stimulus is given in the pattern of the amounts of response across the neurons, rather than the response of individual neurons. A question of major importance however, is whether cell populations in this scheme are subdivided into groups of identically reacting receptor cells or whether the cells' spectra is distributed randomly (Boeck, 1980). All such theories are related to topographic organisation, by which a stimulus characteristic is represented in an orderly way across neural areas.

Temporal coding is concerned with the relationship between the rate of neuronal firing at different points in time, or the rate of change in frequency. It is difficult to imagine a complete temporal coding strategy that may be utilised by the olfactory system and would satisfactorily explain the range of observed properties. It seems eminently more plausible to expect that the neural coding employed by the olfactory system is spatio-temporal in nature, and not rigidly confined to one or other of these narrow concepts.

Coding in the olfactory system - Receptor level

Information theory has provided us with the concept of coded messages. Originally developed in the late 1940's by two wartime research officers (Shannon & Weaver, 1949) its applicability to sensory systems is apparent. In the case of olfaction, information is transmitted from the environment in the form of odour molecules to the receptor system which can be interpret the message because it "knows" the rules, i.e., the code by which the information is contained in the message. A recent concept suggested by Shepherd (1991) is that the olfactory system performs a number of computations on input to produce a series of "molecular images" corresponding to activity maps at each stage of processing.

What follows is a brief investigation of the coding taking place at the level of the primary receptors. An important caveat is that the concept of a code must not be confused with a description of stimulus evoked activity. At each stage in the processing of olfactory information, neural activity will contain relevant and non-relevant components which require separation. Furthermore, it is important to realise that we do not know *a priori* which properties of the stimulus are relevant to its coding in the nervous system. We know which stimulus characteristics are relevant to humans, intensity, quality, hedonic tone, but not how these are evoked by the stimulus.

Considering that it seems likely that the neuronal response to an odorant is of a spatio-temporal nature, three aspects of the peripheral receptor level may play a greater or lesser role: the selectivity of receptor cells; the spatial response pattern across the mucosa, and the organisation of the primary projections to the olfactory bulb (Sicard, 1989).

When an odorant is inspired and the odorous molecules bind to receptor proteins in the olfactory epithelium, the receptor cells spontaneously alter their discharge frequency. In the epithelium of amphibians, the time course and latency of such a response is dependent on the concentration of the odorant, the time course of stimulation and levels of mucus available for absorption (Holley, 1991). As noted previously there are good reasons for supposing that a similar process may occur in humans. With prolonged and strong stimulation of an odorant the generated activity patterns are complex. Without further complications of trying to decide what constitutes a "pattern" for the olfactory system, it would seem that the phases of suppressed activity followed by activity, and the decrement of spike amplitude in response to intense stimuli do not represent a code but intrinsic activity of receptor cells. The only code that has been demonstrated according to Holley (1991) is that between intensity and frequency.

The relationship between concentration and frequency has also been modelled, the response increasing with concentration, although certain findings suggest that the range of receptor cell effectiveness could be broader than previously thought (Van Drongelen, 1978). Although the phenomenon of olfactory adaption is well known in the

psychophysical literature, its effects on the human olfactory epithelium are less easily demonstrated.

In vertebrates, the main finding concerning the temporal response of the peripheral receptor system has been that most cells display a broad band sensitivity. They give excitatory responses to a wide range of odorants and electrophysiological studies have consistently found that some can discriminate amongst sterically related molecules that elicit similar odour perceptions in humans, but no two receptors have identical response spectra. Thus, there is no basis for classifying receptor cells on the comparisons of their response spectra (Moulton, 1978). This broad, overlapping spectra of individual neurons is thought to be necessary for discriminating different odours independently of concentration (Shepherd, 1991). The same phenomenon can be seen in vision, where individual cone receptors have broad, overlapping spectra but whose adsorption curves peak at different wavelengths. This is thought to aid in the discrimination of wavelength independent of intensity.

Thus, in terms of the concept of molecular images suggested by Shepherd, it would seem that different parts of the receptor sheet are activated by odours, reflecting differential adsorption and binding rates. Such activity produces spatial activation patterns, that in turn, depend upon the type and number of available molecules.

Regarding the spatial pattern across the mucosa, it is important to note that there is a distinction between "imposed" or "extrinsic" selectivity gradients and "inherent" or "intrinsic" gradients. Imposed patterning refers to the distribution of odorants over the surface of the epithelium. Inherent patterning refers to the property of some odorants to be maximally effective at certain portions of the mucosal surface, often called "chemotopy" (Holley, 1991). Such a theory, that implicates spatial patterning as a component of odour quality coding at the receptor level, would be expected to lead to some kind of topographic projection to the olfactory bulb, the next level of olfactory processing. Recent studies would suggest that some degree of region to region

projections following some kind of topographic organisation do in fact occur (Astic & Saucier, 1986).

The principle of chemotopy does not seem compatible with distributed information (which implies dispersion and non-localisation) that we have already seen operates in the mucosa. In fact, it would seem that there is *some* degree of chemotopy that modulates the distributed form of information from the olfactory epithelium. To conclude that coding at the primary receptor level is spatially organised would be premature and probably mistaken. The odour quality coding that occurs at this level of the olfactory system involves extrinsic and intrinsic patterning, they coexist, and may act in concert. Thus, the number of activated receptors indicates the intensity of the odour, and the location of the activated neuronal population indicates the nature of the odour (Freeman, 1991b).

One fascinating aspect of the coding relationship between the receptor cells and the bulb is that it seems likely that events late in the receptor sheet are filtered out by the bulb which suggests that receptor cell spikes have differing effects on the coding of odour, dependent upon their temporal profile (Holley, 1991). Intraglomerular mechanisms also have a role in the control of input, in that excitation becomes less efficient with increases in the flow rate of afferent pulses. Holley (1991) suggests:

" Input control and transmission limitation can be seen as complementary to the sensitivity increase caused by convergence, in that they tend to counterbalance the amplifying effect and stabilize the olfactory message with respect to concentration changes ." (Holley, 1991: 338)

Coding in the olfactory system - Bulbar level

The discussions of chemotopy above suggest that there is enough order and local structure in the projections from the olfactory epithelium, to provide the basis for a further molecular image. Such an image could be mapped from the activity pattern of the receptors, to the glomerular layer of the bulb. Shepherd (1991) reviews the empirical evidence for this mapping process, and concludes that:

"...the patterns have sharp foci and complex spatial structures reminiscent of the complex structure of the anatomical projections. The high degree of order in the functional patterns in the glomerular layer thus mirrors to a surprising degree the order in the anatomical patterns of projections from epithelial regions." (Shepherd, 1991: 23)

Perhaps the most important recent development regarding the coding of olfactory information, is the idea that the olfactory glomerulus forms a functional unit. This has yet to be established but if it were the case, then the mitral cells innervating a glomerulus would have the same response spectra and the number of independent output channels would be equal to the number of glomeruli, not relay cells (Holley, 1991). There are important pieces of information that suggest glomeruli are not only vital in olfactory processing, but also form functional units. This is their modular organisation and their presence at the first synaptic relay in the olfactory pathway. Shepherd (1991) has suggested a role for such units, namely mediating grouping and discrimination processes. He notes that grouping functions could arise as a result of the compression of inputs occurring at this level. Receptor neurons converge onto single glomeruli with a ratio of 25,000:1 which could account for the sensitivity of olfaction processes. Further discrimination could occur within and/or between glomeruli.

The third stage of processing occurs in the external plexiform layer of the olfactory bulb containing the mitral and tufted cells. Of limited relevance to odour coding are the altered responses in the excitatory and inhibitory activity of mitral and tufted cells occurring during experimental procedures, such as exposing the epithelium to odorants,

when stimulation and breathing are uncoupled. Normal breathing enables the system to reset by the modulated input from receptor cells.

In freely breathing, awake animals, Chaput & Holley (1985) discovered that odour stimulation may not produce increased spike emissions, but that the firing rate increased at the end of inhalation and decreased during exhalation, resulting in the fact that the overall bulbar output changed little. Inhibitory responses in mitral cells is thought to be associated with high stimulus intensity.

It is thought that mitral and tufted cells process different information in parallel. The empirical evidence suggests that the molecular image at this level is generated by the connections between mitral and tufted cells and the glomeruli. Also having influence are the inhibitory connections of the granule cells.

Further evidence of bulbar activity comes from lesion experiments. Many studies have shown that animals with massive lesions in the bulb still retain the ability to detect and discriminate a wide variety of odorants (Tagaki, 1989a). Obviously this is not compatible with an entirely spatial view of odour processing. However, it is possible to conceive of a model that incorporates some degree of spatial coding. It may be that information from the receptors is repeated in different parts of the bulb. So the lesions may destroy a particular subsystem that receives information, or lead to impoverished input to several subsystems, but other subsystems are still receiving adequate input allowing tasks of detection and discrimination to go ahead. However, it may be that, in their natural habitat animals are expected to distinguish between subtly different odours and further to detect odours at low concentrations from a high odour background, so presenting lesioned animals with tasks of equivalent difficulty may reveal important deficits not evident so far.

A further feature of the bulb is that it mediates contextual information about the state of the animal. Information concerning the physiological state of the animal such as thirst or hunger could do this. Further, there is selective enhancement of bulbar response to

odours that are biologically relevant or have acquired relevance during the lifetime of the animal.

Consideration of the spatial coding occurring in the olfactory bulb can only be presented when the projection areas have been examined. If the projection areas make use of spatially oriented information then it can be maintained that some form of spatial coding is operating in the bulb.

Structure, function and coding in olfaction - Secondary olfactory connections

The primary connections of the olfactory bulb mitral and tufted cells are to the primary olfactory cortex, divided into five parts that include: the anterior olfactory nucleus; the olfactory tubercle; the pyriform cortex; the amygdala, and the entorhinal area which projects to the hippocampus. All these areas are part of the paleocortex, but olfactory information is ultimately relayed to the thalamus and neocortex. The olfactory tubercle projects to the medial dorsal nucleus of the thalamus, which in turn projects to the orbitofrontal cortex. The amygdala and hippocampus are part of the limbic system, which is thought to be involved in the affective component of odours, while the thalamic-neocortical projection is thought to mediate the conscious perception of an odour. Unfortunately the physiology of the olfactory cortical regions has not been studied extensively and consequently even less is known about the information processing at this level of the olfactory system, or of the coding strategies involved. Most available, reliable evidence has been gained from a study of the pyriform cortex, so most of the following discussion will concentrate on this area. More speculative comments concerning higher structures will be left to the end of this chapter, where we consider what kind of olfactory related information may be available to be detected and de-coded by EEG techniques.

Several authors have provided a detailed explanation of the neuronal circuitry of the pyriform cortex and its functional implications (Haberly, 1985; Ketchum & Haberley, 1991) and what follows are the implications for olfactory coding. Haberly's theory is

considered further in Chapter 3 when the concept of a "neural network" has been fully explained. In common with all sensory systems selectivity is enhanced at each successive level, and this does seem to happen in the olfactory system. Olfactory receptor cells, distributed widely in the epithelium, converge on to the glomeruli of the olfactory bulb and pyramidal cells in the pyriform cortex receive synapses from several olfactory bulb output neurons after which a wide network of association fibres ensure that olfactory messages are widely distributed. The convergence of afferent fibres in these two structures suggests an integrated system modulated by feedback and lateral inhibition.

Thus, one question that can be asked is, "how are odorants coded at each level ?" One advantage that olfaction enjoys over other senses, is that the second and third order neurons are available to code stimulus qualities such as intensity or quality. Because odours do not have to be localised in the external environment, location is not encoded spatially by the receptor sheet (Cattarelli, 1989). Both physiochemical and electrophysiological studies have indicated that spatial patterns at receptor sheet level primarily encode molecular information and that the selectivity of the olfactory bulb is higher than at receptor level (Duchamp-Viret , Duchamp & Vigoroux 1989). This would indicate that quality coding is occurring spatially, at the bulbar level. Stimulus intensity can be coded by spike frequency by each olfactory neuron, and, as with vision and audition, intensity can also be spatio-temporally coded. This is because extreme variations in stimulus intensity requires the participation of further populations of neurons (with different ranges of sensitivity). Metabolic studies of the olfactory system have shown overlapping patterns of activity in the olfactory bulb related to different odorants. However, corresponding patterns have not been found in the pyriform cortex, which suggests that any transferred information has been redistributed.

Haberly (1985) has attempted to integrate such findings and to model the role of the pyriform cortex in olfactory discrimination. What follows is a brief summary of his ideas, which form the basis of a rather elegant and plausible theory. He suggests that

olfactory information is in the form of a highly distributed "ensemble code" in the pyriform cortex which implies the involvement of the whole neuronal population at the pyriform level. Evidence suggests that the circuitry here differs markedly from that found in the primary sensory areas in the neocortex. This is consistent with a requirement for a different kind of information processing. Its organisation is similar to that found at higher levels of the neocortex and Haberly (1985) explains this:

"The highest order areas of neocortex in terms of the information processing hierarchy are very likely the most primitive phylogenetically." (Haberly, 1985: 231)

Haberly (1985) further suggests that the role of the pyriform cortex is to act as a content-addressable memory for the association of present odour stimulation with memory traces of previous odours. Models of simple neural network models, physiologically plausible, have shown that they can store spatially distributed patterns by adjusting a series of weights representing synapses. Features of such models include an ability to recognise degraded patterns and an ability to generalise patterns, in other words, to associate. Furthermore the circuitry of the pyriform cortex meets the assumptions that underlay such models, such as a large number of integrative units; a highly distributed input; positive feedback through myriad interconnected units; and synaptic reinforcement through repeated exposure to an odour.

Although the coding occurring at the higher levels reached by olfactory information is not yet available, it is still possible to suggest what kind of processing may be taking place. The best way to achieve this is by examining lesion studies which allow the identification of neural pathways important to olfaction and may further suggest the nature of olfactory perception.

Anatomical work with animals has verified the presence of projections from the pyriform cortex to the mediodorsal nucleus in the thalamus, which opens up the possibility of projections to the orbitofrontal cortex. Lesion studies in rats suggest that there are two pathways taken by olfactory information: thalamocortical, and amygdalohypothalamic

(Engen, Gilmore & Mair, 1991). The first of these, the thalamocortical, plays an important part in the discriminatory process, while the links to the hypothalamus are important for the regulation of feeding and neuroendocrine functions. These and other studies, are consistent with the view, that serial reversal learning of an olfactory discrimination, is impaired by the blockage of the thalamocortical links. This is consistent with evidence from other sensory modalities, which suggest that impairment of reversal learning occurs after these links are destroyed (Engen et al, 1991).

The possible role of the hippocampus is less well understood. It seems unlikely as a candidate for a specific olfactory pathway but it receives afferent input from the entorhinal cortex, which in turn receives input from the olfactory bulb. Lesion studies have shown complex results and to date no firm conclusions have been reached regarding hippocampal involvement in the processing of odours (Engen et al, 1991).

Clinical studies indicate that anosmia results from peripheral rather than central lesions. If the olfactory bulb and its immediate projections are damaged then anosmia will result. Anosmia is the loss of the ability to smell. More central brain lesions can impair discrimination and quality coding but leave intact the capacity to detect odorants. Studies that show olfactory deficits produced by lesions of the temporal lobe, are difficult to interpret. This is because the temporal lobe contains most of the primary projection areas from the olfactory bulb. Thus, it is unclear what may be the anatomical basis for the deficit (Rausch & Serafetindes, 1975; Eskenazi, Cain, Novelly & Friend, 1983). Lesions involving the frontal lobe are similarly subject to problems of interpretation, because of the large amounts of tissue removed in lobectomies in this area, and the effects only appear when olfactory projection areas have been removed (Potter & Butters, 1980; Jones-Gotman & Zatorre, 1988).

Patients with Korsakoff's disease show an impaired ability to discriminate odours, without any loss in detection ability. Two neural mechanisms have been implicated in these patients, lesions of the mediodorsal nucleus that affect the thalamocortical pathway, and lesions that affect ascending norepinephrine which contains neurons that innervate

the olfactory bulb and related forebrain structures (Engen et al, 1991). Korsakoff's syndrome is probably the best studied of all central olfactory deficits but:

"There is no empirical basis at this time to determine whether the basic deficit involved discrimination per se or an impaired capacity to utilise olfactory information in making conscious cognitive judgements. In the case of Korsakoff's disease there is a strong basis in other sensory modalities to argue for the second possibility, namely, a sparing of automatic and an impairment of attended perceptual processes ."(Engen, et al 1991: 324)

Neither does it appear that memory deficits can account for the loss in olfactory discrimination by affecting the decay time in short term memory. Such patients cannot discriminate between different odours in tasks designed to reduce the load on short term memory and they are still able to match pictures to verbal labels but cannot do this with odours (Engen et al, 1991).

Several authors have also suggested that olfaction shows a hemispheric bias, in that the right hemisphere shows superiority over the left (Hines, 1977; Zucco & Tressoldi, 1988; Zatorre & Jones-Gotman, 1990). Despite findings which suggest no such effect (Eskenazi, Cain, Novelly & Mattson, 1986) the weight of present evidence suggests that odours are represented in both hemispheres and that the right hemisphere may have a relative superior capacity for odour recognition (Richardson & Zucco, 1989). However, the findings are often difficult to interpret and as yet no complete anatomical or functional explanation has been advanced to explain the supposed right hemisphere superiority. Further information concerning hemispheric differences in the processing of odours is considered in Chapter 2.

The task in the present thesis is to determine if an "odour image" persists beyond the level of the olfactory cortex to be "de-coded" by EEG techniques. It would seem that the most likely form of this image would be a complex spatial activity pattern. If such a pattern does persist it is probably because of the significance of the odour presented and the

necessity for information to be transferred to and from different brain areas. The next chapter considers what kind of activity the EEG is able to detect and the functional significance of this activity.

Summary

Activity in the receptor cells represents the intensity and nature of the impinging stimulus, and this information is temporally coded but spatially modulated before being conveyed to the olfactory bulb. The bulb imposes a severe restriction on the amount of afferent fibres it receives, transmitting and processing the odour information in vertical and horizontal neural networks before passing the amplified result to higher olfactory areas. The information is of a distributed character but is again spatially modulated. Furthermore, the bulb modulates contextual information and selectively amplifies input. The secondary projections do not form a coherent structure, but receive different portions of the bulbar output, the main recipient of information being the pyriform cortex, which uses a postulated ensemble code. It has been indicated that the structures along the thalamocortical pathway mediate cognitive perception of odours, whereas those in the amygdalohypothalamic route mediate affective responses to odours.

CHAPTER TWO

Electroencephalography (EEG)

Introduction

This chapter of the thesis aims to explore not only the neurogenesis of the EEG but also the issues raised by the technology used in collecting such data. It is also important to be aware of factors, such as attention and arousal, that can affect the EEG and the results of any subsequent analysis. A further issue is the possible distinction between sensory and cognitive effects. Are such distinctions valid ? If so, on what basis, anatomical, physiological or behavioural (Buchwald, 1989) ? It is not the intention to provide a thorough review of the EEG literature here. What is provided below is an attempt to draw together some of the threads necessary to understand the whole thesis. Therefore, some anatomical and neurophysiological detail is required in order to understand the models proposed to account for EEG function. Also, a discussion of the placement of electrodes, and associated problems, is necessary for a clear interpretation of the results.

The first scalp EEG recordings on humans were carried out by Berger (1929 cited by Offenloch, 1975) who recorded the oscillations of the cerebral currents and in doing so marked the beginning of clinical electroencephalography. Berger's series of fourteen reports documenting his discovery of the alpha rhythm, and his later interest in clinical issues, were the first flowerings of a field that has since seen an amazing explosion of interest and published reports. Unfortunately, the published field of EEG is very much a curate's egg.

The clinical use of EEG records are now routine. EEG is used to diagnose malfunction: brain tumours and epilepsy; diagnosis and prognosis of head injuries and cerebral trauma; brain damage caused by thrombosis; developmental disorders, and the monitoring of the sleep stages (Gevins & Schaffer, 1980). It can also be used to assess the depth of a coma or to confirm brain death. For psychologists, the main area of interest has been to

investigate higher cortical processing using the EEG as an independent or a dependent variable.

The discovery of the EEG rhythm and development of the technology was thought to hold great promise, for localising higher cognitive brain functions such as: perception, memory, attention, language and explaining complex relationships between the brain and behaviour (Gevins & Schaffer, 1980). Progress however has not been smooth and much of the published work is not of a high quality. Perhaps, related to the fact that our understanding of the psychological significance of the EEG is limited, many psychologists have carried out research in this area, lacking appropriate technical expertise and knowledge. Also, some semantic confusion is probable as some of the constructs used have no agreed definition, and are not independently controllable within experimental situations (Low, 1987). Some researchers have suggested that the EEG is not a sensitive measure of brain function, and that the amount of data produced requires specialist interpretation that is not usually available to psychologists (Gale & Edwards, 1983). The single greatest block on the further development of EEG may be the lack of a coherent and precise conceptual framework, to explain the functional significance of the EEG, that is amenable to scientific testing.

Fundamentals of EEG

Cerebral architecture

The human brain is divided into three main parts, the brainstem, the cerebellum, and the cerebrum. The cerebrum is divided roughly into two halves and the outer layer is known as the cerebral cortex. This cerebrum is what distinguishes humans from their most closely related vertebrates and one of the challenges for neurobiology is to understand how the organisation of the cortex relates to functional behaviour and higher cognitive processing (Martin, 1985). For the purposes of understanding what kind of signals are received by scalp electrodes for an EEG, it is important to know something of the anatomy, cellular characteristics, and processing features of the underlying tissues. All,

but the lowest magnitude, electrical potentials recorded on the scalp are thought to arise from the cortex (Nunez, 1981).

The cortex is approximately 2-4 mm thick, with a total surface area of approximately 1600 cm^2 (Nunez, 1981). It is organised into infoldings called fissures and prominences called sulci. The most prominent sulci can be used to divide the cortex further into four lobes: frontal, parietal, temporal and occipital. Large areas of the cerebral cortex are devoted to sensation, movement and higher cognitive functions. Many excellent reviews and text-books have covered the functional anatomy in great detail (Nunez, 1981; Gevins & Schaffer, 1980; Kandel & Schwartz, 1985).

The most striking morphological feature of the cerebral cortex is its organisation into several well defined layers that run parallel to the surface of the brain. In general, the cortical neurons can be classified into two broad classes: pyramidal cells and stellate cells. Pyramidal cells are the major output neurons, with conical bodies and dendrites of up to 500µm or more in length. The dendrite leaves the apex of the cell body and projects towards the pial covering of the brain, intersecting the layers at roughly right angles. From the base of the pyramidal cell, which may be up to 30µm across, giving the cell a pyramidal appearance, a number of dendrites project laterally within their containing layer. On structural grounds pyramidal cells with their long dendrites seem designed for carrying output from cortical areas, and to have a limited role in local processing via their collateral branches (Kelly, 1985).

Stellate cells are smaller and have rounded bodies. Structurally these cells appear best suited for local intracortical processing of afferent inputs. These cells are approximately 10µm in diameter and their dendrites arise from all parts of the cell body and branch profusely in the cortical layers near to the cell itself. Individual layers of the cortex do not posses equal proportions of these cells and so an important indicator of an area's function is the number and type of cells present (Kelly, 1985). It would seem that an area populated mainly with pyramidal cells would be an output layer, whereas a layer mainly populated by stellate cells would be the principal sites of termination for thalamic and

other afferent inputs. An important type of stellate cell is the basket cell, which forms synapses that envelope the soma of the postsynaptic neuron, and is thought to be inhibitory.

Six layers can be discerned in the neocortex. The most superficial layer, layer I, consists mainly of glial cells whose axonal processes run parallel with the surface of the brain and synapse on apical dendrites of cells from deeper layers. Layers II and III are more densely populated with small pyramidal cells and these layers provide the output for other cortical areas. Layer IV receives most of the afferent input from the thalamus and as such is populated almost exclusively with stellate cells, for the initial stages of processing. Layer V contains the largest pyramidal cells whose processes project to the corpus striatum, the brainstem and the spinal cord. Layer VI projects back to the thalamus. Each cortical area has a distinctive layering pattern because of the expansion of some areas at the expense of others. For instance, a large thalamic input implies a primary sensory area and so area IV is expanded because it contains the cells for initial processing, the stellate cells. In motor areas however, area V will be prominent as the pyramidal cells give rise to long descending pathways at the expense of layer IV (Kelly, 1985).

Studies of the primary somatosensory cortex and the primary visual cortex (Mountcastle, 1984; Hubel & Wiesel, 1962 cited by Martin, 1985) have shown that there are similarities in cortical organisation in the two primary sensory areas. Both systems are organised in vertical columns primarily composed of tens of thousands of small neurons whose axons primarily synapse in the local area. Such neurons are characterised by their extensive dendrodendritic connections (Gevins & Schaffer, 1980) and the cells in each column have similar receptive field positions and responses to an effective stimulus. Thus it would seem that the cortex is a laminar structure organised into repetitive, vertically oriented, columnar units of approximately 300µm in diameter (Katznelson, 1981). Each of these macrocolumns in turn is organised into minicolumns of approximately 30µm diameter (Gevins & Schaffer, 1980).

Gray (1959 cited by Martin, 1985) classified the synapses in the cortex into two types: type I which are excitatory and end on dendritic spines; and type II which are inhibitory and terminate on dendrites and cell bodies. From an information processing perspective it is important to note that inhibitory synapses are located closer to the cell body than excitatory synapses. This means that they exert their influence at the earliest possible time. Pyramidal cells, unlike spinal and motor neurons which are subject to temporal constraints, are capable of high frequency firing, and display a brief hyperpolarising afterpotential. Furthermore pyramidal cells show several trigger zones on their dendritic trees which serve to boost remote excitatory inputs. This is especially useful when you consider the length of the dendritic processes from a pyramidal cell. This is in contrast to spinal neurons which posses a single spike-initiating zone near the soma meaning that distant inputs have a considerably weaker influence on any spike generation.

To some undetermined extent our awareness of internal and external events must involve the interaction of the cortical neurons described above. The problem for researchers is to relate the electrical potentials recorded on the scalp to underlying physiological and psychological processes, and further relate any changes in the observed scalp patterns to different experimental manipulations.

Neurophysiological mechanisms

Any researcher who does not have a background in the physical *and* the biological sciences must be wary of the multitude of possible mistaken assumptions when dealing with EEG data. In this respect many researchers are greatly assisted by the work of Nunez (1981, 1990) who has done much to close the gaps in communication between these sciences and continually reminds us that electrical activity is generated and conducted according to established biophysical principles that should not be ignored.

The electrical activity in the brain can be divided into several categories: spontaneous potentials, this would include the alpha rhythm and sleep rhythms; evoked potentials (EP), or event related potentials (ERP); microelectrode studies of single electrodes; and

the contingent negative variation (CNV) which is a baseline phenomenon (Nunez, 1981). The EEG is not derived from the summated action potentials of neurons, but rather from the summated postsynaptic potentials of the cell bodies and dendrites of vertically organised pyramidal cells in layers III to IV in the cortex (Nunez, 1990). An excitatory postsynaptic potential is a signal of negative polarity, and by causing changes in ionic permeability of the membrane, it produces a local current "sink." A sink is an inward flowing current (a "source" denotes an outward flowing current). In contrast, an inhibitory postsynaptic potential causes a local source of current that flows into the extracellular space. Thus, the electric current that is found in living tissue involves the movement (in opposite directions) of negatively charged and positively charged ions. The flow of an ionic current generated by neurons through the extracellular space can be described by volume conduction theory, developed to describe the electric fields in physical media almost fifty years before the EEG was discovered (Nunez, 1981).

The number of synapses impinging on a pyramidal cell in the cortex can be as high as 10^4, and each area of cortical tissue equal to approximately $1mm^2$ can contain up to 10^5 pyramidal cells which can involve up to 10^9 synapses (Nunez,1990). The pattern of ionic flow at the micro level would be very confusing but the more macroscopic view provided by the EEG holds that areas of cortex up to $1cm^2$ can be said to form a single dipole source. Dipole layers must also be considered as a source region for macroscopic studies (Nunez, 1990). A deterministic dipole layer is made up of parallel dipoles with synchronised activity and most spontaneous EEG is due to a cortical dipole layer formed by pyramidal cells. The electrical activity picked up by electrodes on the scalp comes from at least three sources: summated postsynaptic potentials; single dipoles; and dipole layers. The researcher looking at scalp potentials is unable to resolve the neural activity below the scalp that corresponds to a single cortical column, but only the activity that relates to thousands of columns which, in turn, involves the activity of millions of neurons.

One of the most interesting models proposed to account for the dynamic behaviour of neurons at the macrocolumn level has been proposed by Freeman (1975, 1987, 1991a, 1991b) and relies on the spatial distribution of amplitude, frequency and phase of macropotentials.

A basic property of Freeman's model, is that populations of neurons work in synchrony, which depends upon the level of interconnections. Freeman (1975) has developed a nomenclature for this model. Populations of neurons with mutual interactions are called KI sets, and these can be inhibitory (KIi), or excitatory (KIe). If these two neuronal populations interact they are known as a KII set. KIII sets can then be formed by the interaction of two KII sets. A neural mass is considered to be a number of such KIII sets, consisting of an estimated 10^4 to 10^7 neurons (Lopes da Silva, 1987a). Feedback loops, both excitatory and inhibitory are incorporated into the model. The parameters of the behaviour are: temporal consequences of synapses; distances between different neurons; and the strength of such interactions (Freeman, 1975). Using sets of coupled differential equations that incorporate static non-linear functions, Freeman has mathematically modelled the dynamics of the olfactory structures of the rabbit (Freeman, 1975). The simulated EEG recordings approximate the actual EEG recordings. Thus at this level (olfactory bulb and olfactory cortex) it can be demonstrated that the EEG carries behaviourally relevant information. Experimental gaps still remain however, as despite the inspired work of Freeman, corresponding studies of the human neocortical EEG remain to be performed and then such work has to be related to the potentials observed on the scalp.

The signals that reach the scalp however, have been "smeared" i.e., changed by their passage through intervening brain tissue and attenuated because of their passage through the skull and scalp. The calculation of scalp potentials from known sources is known as the forward problem in EEG research, but there is also the inverse field problem which is to locate sources given the spatial and temporal distribution of potentials over the scalp. The inverse problem however, has no unique solution, there exists an infinite set of

possible source locations and configurations all of which give rise to the same potential distribution on the scalp (Katznelson, 1981). Most of the present day EEG research is devoted to examining potentials distributed over the entire scalp which necessarily will involve many sources. As a result the recording methods and the interpretation of results should be independent of any assumptions of a localised source.

Electrode placement, reference electrodes and wavebands

A continuing problem in both EEG and EP research, is choice of electrode placement (mostly made of, or coated with, gold or tin). Berger used electrodes at the front and back of the head but it was soon discovered that EEG activity differed at different locations on the scalp. In 1958, the Committee of the International Federation of Societies for Electroencephalography and Clinical Neurophysiology (IFSECN) recommended a standardised 10/20 system of electrode placement (Jasper, 1958). This meant that electrodes had to be placed on specific anatomical landmarks from which measurements could be made and further electrodes placed at 10 or 20% of specified distances. The system allows the further addition of electrodes, above the 21 recommended by the American EEG Society (Reilly, 1987). The standard numbering system places odd numbered electrodes on the left and even numbers on the right with accompanying letters to designate the underlying cortical area. This pattern of electrode placement is often known as a "montage." A basic property of an electrode is that it should have a metal and liquid junction in the gap between the tissue and the recording apparatus itself. In scalp recordings such as the present study, contact is established by electrode jelly that makes an electrolyte bridge (Kamp & Lopes da Silva, 1987b).

The decision as to how many electrodes to use can be based on factors such as the type of montage used, the target population, the type of activity studied, aims of the experiment, etc. A general guide-line is to use as few electrodes as possible without jeopardising the quantity of information needed to answer the question in hand. A further question concerns the relationship between the electrode positions on the scalp and their anatomical correlates. Recent research by Myslobodsky, Coppola, Karson, Daniel &

Weinberger (in press, cited by Coppola, 1990) has indicated that the use of bony landmarks and the 10-20 system does not guarantee alignment of actual brain structures. There is often a deviation of the posterior midline in up to 50% of normal brains and the placement of electrodes relative to the inion does not provide a symmetric alignment with the poles.

The choice of a reference electrode is much more problematic and is the cause of much confusion and doubtful interpretation of EEG scalp potentials. Two problems combine to make this choice difficult. In most studies the recording electrode may well be placed at least 1 cm from the source of the recorded potential and so the distinction between the recording electrode and the reference electrode is lessened. Also, the potential generated by a local source "smears" because of the poor conducting properties of the skull. As a result the potentials observed on the scalp should be seen as derived from global as well as local sources (Nunez, 1990). Scalp recordings always measure the potential between two locations. If the electrodes are close together, then there will be a fairly reliable estimate of the underlying scalp potential, if they are distributed over a large area then the underlying scalp potential will be measured over a larger region. However, it seems that no sharp distinction exists between a reference and a recording electrode (Katznelson, 1981). Linked ear or mastoid reference electrodes are widely used in EEG and ERP work, but both have associated problems (Katznelson, 1981; Nunez 1990). Katznelson (1981) suggests that the best site for a "reference" electrode is at the neck, eliminating the possibility of any contamination of the EEG record with cardiac (EKG) current (Nunez, 1981). Katznelson (1981) summarises as follows:

"In all of the methods discussed above we record potentials at any point with respect to some reference. By definition, potentials are results of integration of the electric field over any path connecting the reference point and the point in question. The potential at any point is not a characteristic of that point but rather a characteristic of the path to that point. Hence by recording potentials we are not observing a local property pertaining to the location of the electrode." (Katznelson, 1981: 195-196)

The average reference method has become more widespread because of the availability of powerful computing facilities. However, this method can produce further complications because the potential corresponding to a given scalp location, depends on where all the other electrodes are located. If the signal is underneath one or two electrodes the resulting pattern may be spread across the whole head. Laplacian transformation produces a "reference free" display but can result in low spatial frequency information being lost. The difference potential between electrodes is used to compute the curvature of the field, which represents the current flow (Hjorth, 1975; Mackay, 1984; Coppola, 1990). Furthermore, this method can involve some heavy computational work (Nunez, 1981). Thus, there is no one agreed or universally accepted method.

The EEG has been described as "the continuous roar of the brain" (Niedermeyer, 1987a: 97) but in fact some order does exist in the generated frequency spectrum. However, the harmonic structure of the EEG is complex and it rarely approaches a sinusoidal form. The classification of the frequencies into five bands has arisen by convention and can best be seen in an historical context. Berger introduced the term "alpha" (8-12 Hz) and "beta" (above 13 Hz). The term "gamma" (above 30-35 Hz) was introduced by Jasper & Andrews (1938 cited by Niedermeyer, 1987a) but has subsequently been absorbed into the beta category as beta II. The term "delta" (below 4 Hz) was introduced by Walter (1936 cited by Niedermeyer, 1987a) to include all frequencies below the alpha range. He also designated the term "theta" (4-7 Hz) ignoring several Greek letters in order to denote a rhythm he thought determined by thalamic input (Knott, 1976). Often an EEG record is contaminated by physiological and instrumental artifacts arising from muscular movements, cardiac rhythm or an unsatisfactory electrode contact on the scalp. Removal of such artifact is discussed further on in this chapter.

A discussion of the various wavebands is required because, any effects found in the present study that may be restricted to one band should be explained in terms of a hypothesized neurophysiological link. This is especially important when you consider that the distinction between such bands have only arisen by convention and that any

functional significance present in the EEG may be spread across putative boundaries between these wavebands. The definition of alpha rhythm has been proposed by IFSCEN (1974 cited by Niedermeyer, 1987a):

"Rhythm at 8-13 Hz occurring during wakefulness over posterior regions of the head, generally with higher voltage over the occipital areas. Amplitude is variable but mostly below 50 μv in adults. Best seen with eyes closed and under conditions of physical relaxation and relative mental inactivity. Blocked or attenuated by attention, especially visual, and mental effort." (Niedermeyer, 1987a: 98)

The frequency of the alpha rhythm is approximately 10 Hz, which is reached at aged ten and maintained into adulthood. Alpha amplitudes however vary a great deal between individuals and within the same individual over time. Alpha is often more prominent in males but this gender difference is small (Matsuura, Yamamoto, Fukuzawa, Okubo, Uesugi, Moriiwa, Kojima & Shmazono, 1985). The maximum alpha amplitude is located over the occipital area although it can extend into mid-temporal and central regions. The appearance of alpha in the frontal region indicates contamination from a referential ear or mastoid electrode (Nunez, 1981). It would seem that the alpha amplitude is mildly higher on the right hemisphere (Simon, 1977 cited by Neidermeyer 1987a; Peterson & Eeg-Olofsson, 1971). The alpha rhythm is mostly characterised by a sinusoidal waveform but this is not universal. Alpha attenuation occurs with the presentation of auditory and somatosensory stimuli, but this effect is not as pronounced as that found with visual stimuli. It can be hypothesized at this point that some alpha attenuation may occur in the present study, but to date the author is unaware of any study demonstrating this after the presentation of a chemosensory stimulus. The main indicator of vigilance is the suppression of the alpha rhythm, so the presence of alpha indicates relaxed wakefulness. In the early stages of sleepiness, the alpha rhythm drops out and is replaced by frequencies such as theta (Westmoreland & Klass, 1981). Many researchers show a preoccupation with the alpha frequency which may be misleading, when you consider

that most human behaviour does not usually take place in a state of relaxed wakefulness. As to the theoretical question of the generation of the alpha rhythm:

"No neurophysiological or psychophysiological alpha rhythm theory has yet found general acceptance, and there are still uncertainties about the origin and psychophysiological significance of this remarkable phenomenon." (Niedermeyer, 1987a: 103)

The beta rhythm includes recordings over 12-13 Hz, but limitations of the technology mean that the upper limit for most recordings is about 40-70 Hz. The beta rhythm is prevalent in normal healthy adults especially when a person is involved in mental or physical activity (Andreassi, 1980). Some suggestions that beta may be a correlate of focused attention (Low, 1987) may be related to the disappearance of the alpha rhythm which makes the beta rhythm seem more prominent. Some discussion has centred around the relationship between beta activity and personality types but as yet no reliable evidence exists (Niedermeyer, 1987a). Matsuura et al (1985) have found that beta activity is more prominent in females but that the difference is small.

Theta activity is not prevalent in the normal, healthy, awake, adult EEG. It has been reported to occur more often in the spontaneous EEG of children and it reaches a stable adult level at 22 years of age (Matsuura et al, 1985). The delta wave is a large amplitude, low frequency wave appearing in normal adults in periods of deep sleep (Andreassi, 1980). The appearance and prominence of these rhythms in a testing situation would indicate drowsiness.

Topographic brain mapping of the EEG

Increasingly powerful technology has been brought to bear on the electrophysiological study of the brain, especially in those studies that use multi-lead data. As early as the 1950's toposcopes had been developed to aid the clinician in making judgements about the spatial and temporal nature of EEG data. Petsche (1989) has provided a review of these early, and later attempts. Duffy, Burchfiel, & Lombroso (1979) point out that the EEG record is a complex spatio-temporal affair and that making assessments of such activity by eye, i.e., as in the traditional methods, is of limited clinical utility. They were the first to develop a relatively cheap and "simple" method whereby the electrical activity from scalp potentials is displayed in the form of coloured maps. Petsche (1989) says:

"In spite of all developed, highly sophisticated methods.. the human mind will never be able to renounce such a direct observation of the electrical events." (Petsche, 1989: 27)

The view of Sherrington (1946) elaborated in the quote below is perhaps a reminder as to why viewing the on-going events of the brain is so seductive, and why such techniques have acquired a foothold in the EEG field:

"the head mass becomes an enchanted loom where millions of flashing shuttles weave a dissolving pattern, always a meaningful pattern though never an abiding one; a shifting harmony of subpatterns." (Sherrington, 1946: 46)

The first questions to be considered here are those that concern the actual construction of topographical maps and how they relate to the original EEG data. Some fairly serious criticisms of this technique have been made, mainly related to the detection and elimination of artifactual contamination (Walter, Eventon, Pidoux, Tortat & Guillou, 1984; Kahn, Weiner, Brenner & Coppola, 1988; Coburn & Moreno, 1988). These will be considered in so far as they relate to the present study. The analysis of topographical data is a topic worthy of discussion in its own right and so will be presented in Chapter 4.

One of the reasons why topographic mapping has become more prevalent in the last decade has been the advent of small but powerful computing facilities, a necessary ingredient of any mapping system. An important caveat to bear in mind when considering such systems is that the generation of maps does not constitute an analysis procedure. Wong (1991) notes that:

"Topographic methodology involves the additional concepts of digital signal processing, computer graphics and cartography, numerical and statistical analysis, physics of electric fields and quantitative EEG." (Wong, 1991: 2)

It is without doubt a complicated field and only the salient features of the methodology will enter in to the discussion here.

When multiple electrodes are placed on the scalp, they pick up the EEG signal which is then amplified and filtered. This signal is in analog form so it is then converted into digital form (known as AD(C) conversion) so it can be readily stored on a computer hard disk drive. The sampling rate and the precision of this conversion are of maximum importance in order to avoid aliasing artifact. This arises when a signal containing a high frequency is sampled at too low a rate. In order to convert the analog signal (continuous) into a digital one (discrete) which can be represented as a series of numbers to suit the computer hardware, the EEG must be "sampled" adequately enough to capture high frequencies but low enough to avoid overloading the limitations of the storage capacity of the computer (Coburn & Moreno, 1988). In theory the minimum sampling rate should be twice the highest frequency point contained in the signal. In fact, many researchers suggest that this should be increased to five times the high frequency end of the bandpass to ensure accuracy (Lehmann, 1989). It is important to be aware of the possibility of alias error because it is unpredictable and impossible to correct for.

The precision of the conversion is expressed in "bits" which represents a given voltage level. A precision of 8 bits means that there can be 256 voltage levels, while 10 bits means that 1024 levels are represented. The dynamic range and the minimum AD(C)

voltage accuracy must be considered at this point. If 8 bits are used to represent a range of 512 μv then the absolute AD(C) voltage error is 2μv. If larger voltage levels are encountered then the error may be too large and so the need to increase the number of bits arises. In many modern mapping systems such changes may be impossible or restricted because of the electronic hardware used.

The most important asset of a topographical mapping system is the ability to convey spatial information over time. By using a representation of the scalp and presenting successive windows of mapped amplitude activity it is possible to construct a picture of on-going EEG activity. To assist the process of visual interpretation each of the maps are colour coded, by letting a colour represent voltage amplitude. The dynamic range is equally divided into voltage bins, so that a given colour can be used to show all of the values falling into that bin. The use of colour in this technique has been considered controversial by some (Duffy, 1989b) because of its potential to emphasise distinctions that do not exist, or the use of a juxtaposition of colours that could mislead. So when using topographic mapping it is important to use colour properly to emphasise the gradients and to avoid the use of repeating colours. Many mapping machines average the data over a given time period, in this study over 2.56 seconds. By using such coarse time-windows, certain changes to the field over time are lost but the significant EEG activity pattern is retained.

As to the question of the number of electrodes to be used, it remains the case that it depends upon the purpose of the study. For the present study, the number of electrodes used, 28, was ideal. As the sense of olfaction has no demonstrated presence on the neocortex, there was no reason to anticipate a localised source in response to an olfactory stimuli, therefore a sufficient spread of electrodes over the scalp would show if an area of electrodes responded preferentially to different odorants. This is definitely not equivalent to locating a source of the generators mediating olfaction. This would be virtually impossible using this technique. The mapping procedure gives a crude approximation of the events (signals) just below the scalp; these events have been distorted because of their

journey through brain matter, fluid, skull and scalp; and there is no unique solution to the inverse problem as outlined above.

The method of interpolation that is used in the construction of the maps has a great impact on the final appearance of the map, but the optimum method has yet to be agreed upon (Duffy, 1989b). The interpolation procedure is used to "fill in the gaps" between all of the electrodes, to give a complete colour picture. The method used depends upon the number of electrodes used and the weighting factor for each electrode. The number of methods of interpolation almost matches the number of researchers, but the front-runners are: a three or four point linear interpolation; non-linear curve fitting methods (eg.quadratic equations); and inverse distance to the power *n* ; polynomial approximation (Wong, 1991; Duffy & Maurer, 1989). The only method discussed here is the four point linear interpolation as it is the one that has been employed for the present study.

In this case the interpolated values follow the trend set by the bounding four electrodes. One of the consequences of this method is that any peak voltages will never appear in the interpolated region but will only appear underneath one of the four electrodes and may appear to jump from one to the next. This method involves only nearby electrodes and so they are not heavily weighted. The key, according to Duffy (1989b: 21) "is to recall that *all* interpolation techniques are approximations."

Again, the question of the reference electrode has to be addressed, but as holds for classical EEG studies, there is no agreed location for the reference electrode in topographical mapping studies. The isopotential lines in a field display have the same sensitivity to a reference electrode as the traditional EEG paper tracings. In many instances data gathered using one particular reference electrode can be reformatted as if another reference had been used. However, if the data has been decomposed by Fourier techniques, as in the present study, then the resulting maps are critically dependent on the reference used. The maps cannot be transformed because the electric relationship between different locations changes over time (Lehmann, 1989) and the assignment of zero variance might be given to any electrode (Katznelson, 1981). The Fast Fourier

Transform (FFT) decomposes the original signal (time series) into several components such as the five frequency bands discussed above. Although the FFT in itself is not a data reduction procedure it does have the effect of reducing the data in time because it averages over a number of epochs. Mapping of FFT power contains only half of the information originally present, the phase angle information is missing, so a further reduction is achieved. Only data that has first been treated spatially by using average reference techniques can realistically be used for "unique statements about functional-physiological aspects" (Lehmann, 1989: 60). This has clear implications for the present study and will be recalled in Chapter 4, that sets out the underlying justifications, hypotheses and expected findings of this thesis.

A further problem arising from the automatic separation of the EEG signal into five frequency components is that only gross changes in the frequency bands will be detected. Changes occurring within a frequency band that do not result in an overall change will not be detectable. Already research suggests, as above, that the higher frequencies within alpha are responsive to task conditions whereas lower frequencies in alpha are responsive to changes in arousal. Research by several authors (Gale, 1977; Rappelsberger & Petsche, 1988; Lorig & Schwartz, 1989) suggests that the separation of the EEG signal may in fact result in the loss of more subtle changes which may nevertheless be important. Gale (1977) has investigated the EEG changes related to vigilance and concludes that:

"So far as the EEG is concerned, it seems that different frequency bands and even individual frequencies within the traditional bandwidths may be differentially sensitive to different tasks and different situational characteristics. In the present case it appears that high alpha and beta frequencies are more sensitive to discrete changes in stimulation than are the lower alpha frequency and theta activity, which in turn are sensitive to time effects, presence of others, and reflect sex differences." (Gale, 1977: 282)

Findings by Lorig & Schwartz (1989) also imply that the EEG does not form a homogeneous phenomenon, but would better be conceptualised as heterogeneous.

Studies that relate psychological processes to brain activity should consider going beyond the traditional signal separation:

"If research on EEG related to cognition is to progress, it must make full use of the information available in the signal." (Lorig & Schwartz, 1989: 374)

These findings indicate that the interpretation of the results in the present study may be altered by the fact that B.E.A.M does automatically divide the EEG signal into five main frequency bands. This may limit the scope of the findings in that changes in the smaller frequency ranges will go unnoticed and will only contribute to the overall changes in the wide frequency band. The possible significance of this will be discussed in Chapters 4, 8 and 9.

Related issues

Arousal and attention

This sub-section is not an exhaustive account of the effects that attention and arousal have on the EEG. It merely attempts to highlight some of the more important findings that may have a bearing on the interpretation of the results in the present study. The concept of arousal is amorphous and different authors have provided different viewpoints. For the purposes of the present study general arousal will be defined as follows:

"Arousal is seen as an intervening variable that mediates the common effects on performance of several apparently unrelated factors, such as intense noise, incentives, sleep deprivation, time of day, failure feedback and other stressors, intraversion-extraversion and a variety of stimulant and depressant drugs." (Eysenck, 1983: 187)

It would seem that an increase in arousal leads to increased attentional selectivity, but that the effects of different arousing agents are not equivalent (Eysenck, 1983). The concept of attention too, is not simple but Posner (1975 cited in Davies, 1983) suggests three major categories of attention:

"(i) the selection of some information from the available signals for special treatment; (ii) effort, a sense of attention related to the degree of conscious effort which a person invests; and (iii) alertness, an organismic state which affects general receptivity to input information." (Davies, 1983:9-10)

Transitions from one state of arousal therefore are likely to involve some change in the attentional capacity of the organism and such changes can be detected using the EEG which seems to be the most sensitive measure of general CNS activity. It appears that when someone is alert their EEG waves are small and de-synchronised and as the person becomes drowsy and falls asleep then low frequency waves dominate. Most studies report a significant relationship between arousal and changes in the alpha and theta frequencies. Most recent studies discuss arousal under the heading of vigilance or signal detection. In his textbook "Psychophysiology", Andreassi (1980) details the research that has taken place in this area and given below are his main conclusions. Stimulus complexity can affect arousal measured by the de-synchronization of the alpha wave, the more complex the stimuli the longer the de-synchronisation, suggesting that novelty, surprise or complexity can induce increased arousal. The theta rhythm has been associated with an inhibition of distracting stimuli, permitting an increase in focused attention. Finally, an increase in the beta frequency has been demonstrated when the need for structuring incoming information arises.

In relation to the present study, these finding have some significance. All the subjects in this report were alert and awake (although not at a high level of arousal) and not allowed to drowse, a possible hazard as the experimental situation was specifically designed to be of minimum stimulation and as comfortable as possible. Thus, you would not expect to see large amounts of delta in subject EEG records, indicating drowsiness. Also, it may be possible to detect a certain amount of alpha de-synchronisation with the presentation of an unusual odour, representing a novel stimulus.

Gale (1977) has provided a discussion of the findings relating to EEG and arousal and suggests that it is most useful to conceptualise a serial and cumulative model of arousal.

First is the arousal that comes from the characteristics of the subject, such as gender and personality, followed by arousal that derives from naturally occurring rhythms such as the circadian and menstrual cycles. Then there is the manner in which the subject is recruited into the laboratory, the variation in arousal produced firstly by the task acquisition, then task mastery. One must assume also, that there may be task specific changes in arousal, and situational factors that may contribute to an increase or decrease in arousal. Finally there may be changes related to the feedback given in the experimental situation and also the promise of incentives. Thus, at least nine factors may combine differently in each testing situation and in each individual. From the point of view of vigilance studies these factors are of paramount importance but for the purposes of the present study it is only necessary to ensure that the subject maintains a relatively constant level of arousal for the duration of the EEG recording period.

Hemispheric asymmetry

It is important to consider the possible implications of hemispheric effects, that is, to recognise the possibility that some information passing through the CNS may affect or be affected differently by each hemisphere. As early as 1968, Levy-Agresti & Sperry, based on their work with split-brain patients (cited by Dimond, 1977) suggested that the two hemispheres employ different perceptual strategies. There is a vast literature on the the lateralisation of brain function in relation to different tasks, cognitive functions, and different population groups:

"The lateralisation of cognitive functions is not only genetically and ontogenetically fixed and determined, but can also shift depending on the information to be processed. Thus there exists an interactive situation as far as the structure of the brain and the information to be handled are concerned." (Linke, Reuter & Kurthen, 1989: 326)

What is written below is not intended as a comprehensive review of hemispheric differences but a presentation of a suggestive model (Tucker & Williamson, 1984) that combines theories of attention, arousal and emotion. The authors of the model primarily

discuss memory processes, but it appears that the model has important implications for the study of olfaction.

A popular theme in cognitive science is the structure of neural architecture and how this could be related to the information processing capabilities of the human brain. Most of the ideas relating to this will be presented in Chapter 3, which deals with neural network theories. It is sufficient to say that the main controversy involved the invocation of computer models and whether the brain could be considered as the conventional Von Neumann machine, with a central processor and serial operations or the more recent parallel processor machines. What is immediately apparent when the architecture of the brain is examined is that the processing that takes place must be massively parallel in nature.

However, entirely compatible with this idea is the view that certain regions of the brain may have certain specializations for cognitive functions. As a result, certain anatomical differences will be apparent to support these functions. Geschwind & Levitsky (1968) note that a portion of the left temporal lobe is much larger than on the right and speculate that this may be related to the localisation of language functions in this area. Other differences include: the greater width of the right frontal lobe, and the larger size of the left occipital lobe. There are also differences in the manner in which the Sylvian fissure projects in the left and right hemispheres and although the functional significance of such differences are unknown they remain highly suggestive of functional differences (Tucker, 1990). It would also seem that there is a different pattern of interconnections in the left and right hemispheres, the neural fibres in the right hemisphere being more numerous and of greater length (Tucker & Williamson, 1984).

Tucker (1990) has also summarized research that suggests there is a different pattern of receptotopic organisation in each hemisphere. This refers to the distribution of information over the cortex and the supporting theory was first proposed by Semmes (1968) after studying lesions in the somatosensory cortex. Her model is paraphrased by Tucker:

"She suggested that a given region in the left hemisphere is specialized for the integration of like elements, so that the region would handle a single function. In contrast , a given region in the right hemisphere is specialized for the integration of unlike elements, such that any given function has a wider cortical surface representation." (Tucker, 1990: 135)

Goldberg & Costa (1981) have updated this model and suggest that the right hemisphere integrates input from many sources endowing it with a holistic capability and processing style, whereas the left hemisphere is able to focus on input from a single channel and so developed a certain cognitive competence.

Tucker (1990) proposes that each hemisphere is unique in its temporal and spatial patterning and that we must develop network models of different brain areas, and their structural and functional interconnections if we are to understand how the brain accomplishes information processing. He is concerned in particular with attentional controls, namely, tonic and phasic arousal. What follows is a summary of Tucker & Williamson's (1984) work. The model proposes a tonic activation system that is based on dopaminergic control of the basal ganglia, which regulates motor behaviour. The model predicts that at different levels of dopaminergic control different behavioural states will occur, such that too little dopaminergic control will result in impaired motor function, high levels result in action, and extremely high levels will result in routine and stereotypical behaviour. This last implication suggests to Tucker & Williamson (1984) a redundancy bias and as the affective characteristic of the activation system is anxiety, then they suggest that a very high level of anxiety will result in overly focused attention. Their hypotheses in this appear to be supported by the clinical literature (Tucker, 1990). They also suggest that the left hemisphere is primarily driven by this system.

Phasic arousal regulates the brain's response to external stimuli and is seen as the primary mechanism for the orienting response. A feature of this system is rapid habituation and Tucker & Williamson (1984) suggest that the norepinephrine pathways are primarily involved in mediating this response. Such a feature may suggest the right hemisphere's holistic and conceptual capabilities arise, because of the expansional attentive mode and

the lack of concentration on a single element. They further suggest that the affective characteristic of the phasic arousal system is the depression-elation continuum and conclude that:

"With its tenacious control of motor operations, the tonic activation system seems to be especially important to motivational systems; by modulating the brain's responsiveness to external events, the phasic arousal system seems to be integral to emotional processes." (Tucker, 1990:134)

The implications that this theory may have for olfaction soon become clear. Many authors have suggested that the right hemisphere plays a more prominent role in the processing of olfactory information because of its hypothesized non-verbal nature. Also odours are traditionally thought to have powerful links with emotions, (Van Toller, 1988) mediated by the projections of the olfactory system into the limbic system which is involved in emotional processes. Given the supposition of Tucker & Williamson (1984) that emotional processes depend upon the phasic arousal system which is mediated primarily in the right hemisphere, it seems plausible that this is related to the right hemisphere's possible mediation of the affective component of odours. One interesting idea is that emotions may simply be viewed as "flags" on information (Lehmann, Brandies, Ozaki & Pal, 1987). A further supporting idea would seem to suggest itself when phasic arousal is postulated as being the primary mechanism in the orienting response. It has often been suggested (Kendal-Reed, 1990) that the olfactory system functions as a novelty detector and this conclusion would seem to be supported by the above theories of phasic arousal.

EEG data from several electrodes was collected and analysed by Tucker, Roth & Blair (1986 cited by Tucker, 1990) to investigate the hypothesis that if activity in the right hemisphere is of a more diffuse nature and that there are more dense interconnections in the right hemisphere, then this may be reflected in the coherence function of each hemisphere. The general pattern of their results was supportive suggesting that coherence was greater in the right hemisphere. A recent study of the coherence of the EEG of

children, by Thatcher, Kranse & Hrybyk (1986 cited by Tucker, 1990) found a similar pattern of results. Thus, the left hemisphere's involvement in focal and analytical skills is supported by empirical work. Thus, the right hemisphere shows greater functional similarity in EEG response, a reflection of its organisation.

It may be expected then that if a novel stimulus were presented, it would provoke an orienting response that would be primarily mediated by the right hemisphere. It may also have an affective component, which would further implicate the right hemisphere. The implications of the above theories for the present study are presented in Chapter 4.

Sensory versus cognitive events

Based on the previous sections it does not seem possible using EEG measures of brain activity to differentiate between sensory and cognitive events from the derived scalp EEG signals. In fact Lorig (Lorig & Schwartz, 1989: Lorig, 1989) has explicitly warned against such an interpretation of EEG results emphasising that cognitive effects combine with sensory information to produce the observed pattern of activity. Buchwald (1989) agrees and has written:

"I should like to suggest that the territories of these terms [sensory and cognitive] have progressively merged and overlapped as a result of both experimental and clinical observations." (Buchwald, 1989: 242)

It may be impossible to suggest where sensory processes stop and cognitive processes begin, the trick is probably to decipher how these factors combine to produce the activity present at the scalp. It may also be of limited use to try and separate the two concepts. Semantically they differ, but may not when it comes to brain functioning. However, Van Toller, Hotson, & Kendal-Reed (1992) in their studies of EEG and odour perception, have suggested that repeated presentation of the same stimulus to subjects, and averaging the responses, will mean that the individual differences and cognitive effects will be reduced. This will leave a more enhanced "sensory" response, an argument that is similar to that used in the explanation of the ERP methodology, considered in full later on.

Whether this does apply in EEG studies remains to be confirmed. It does seem likely that the recorded EEG signal from the scalp contains both sensory and cognitive components, the question to be answered then becomes, can these signals be averaged or related to the presentation of a particular odour which may indicate a more sensory effect ? These issues are discussed more fully in Chapter 4.

In conclusion, the position taken in this thesis is that it is not possible at this stage to determine from scalp related potential fields the distinction between sensory and cognitive events. If a distinction is assumed at this level, then the basis of the judgement must also be made explicit, i.e., is it anatomical, physiological, behavioural or semantic ? Buchwald (1989) concludes at the end of a detailed discussion of her experiments into the human and cat evoked auditory potential and a consideration of the sensation and cognition processes that:

"Overall, these data suggest that cognitive processes may begin at subcortical levels far in advance of those levels at which sensory processes terminate." (Buchwald, 1989: 256)

This point would suggest that not only is it not possible to distinguish these components of the EEG signal at scalp level, it is not possible at subcortical levels and furthermore it may be a fruitless quest. It is probably much easier to implicate a cognitive process at scalp level rather then a purely sensory one. The whole family of P300's are known as cognitive potentials, as by the length of the latency it is almost certain that the cognitive component will have had an effect on the sensory information. Unfortunately at scalp level it is difficult to suggest that the reverse may be true. The brain is a highly complex, dynamic and highly interactive distributed network that perhaps should not be expected to demonstrate the clear partitioning of sensory vs cognitive, pathways / responses. It may be that these terms have no relevance to the brain, in relation to its functioning and that the distinction that we assume to be clear in semantic usage may not be so significant.

Functional significance of the EEG

The answers to the question of the possible functional significance of EEG findings have often been suggested. The EEG can be seen as cortical manifestation of a central "gating" mechanism, and that the period of the dominant EEG rhythm is an indicator of the speed of information processing. New experimental approaches however, and the work of Freeman suggests an exciting new possibility. Freeman's theory of olfactory processing below neocortex levels suggests that odour specific information is organised as discrete, stable, and spatial patterns of cooperative networks of integrated neurons, and is manifested as spatially modulated patterns of activity in the gamma (20-90 Hz) range (often designated as the Beta II). Bressler (1990) cites work that has discovered similar processes that occur in the visual cortex of the cat (Eckhorn et al, 1988; Gray & Singer, 1989; Gray, Konig, Engel & Singer, 1989 cited in Bressler 1990). Bressler postulates that the gamma wave acts as a cortical information carrier and maintains that the classical description of the EEG response to light as de-synchronisation, may be misleading. He explains:

"Because it is highly attenuated owing to volume conduction through the skull, and because its detection is confounded by scalp muscle activity, brain gamma activity is not easily identified in scalp EEG recordings. What appears as de-synchronization at the scalp may actually be a shift in synchronisation from the alpha frequency to the higher gamma range. Thus, studies associating event-related 'de-synchronization' with attentional processes and those relating gamma activity to focused arousal may be measuring different aspects of a single underlying phenomenon." (Bressler, 1990: 162)

He goes on to hypothesize that gamma oscillation acting in this way as an information carrier may be coordinated in global patterns throughout the neocortex. If this is the case, and Freeman (1989) suggests that it is, then the technology used in the present study and the vast majority of EEG research may be constrained. The optimum range for these high frequency carrier waves is 40-50 Hz, but frequencies above 80 Hz contain significant information in the form of amplitude patterns (Freeman, 1989). It is important to

remember that the 40 Hz EEG has been used as shorthand notation for frequencies in the 35-80 Hz range, usually specified very narrowly (Sheer, 1989). Thus Freeman suggests that 40 Hz activity that is synchronised and may be conceptualised as a limit cycle attractor (discussed fully in Chapter 3) serves as an operator on sensory information, to abstract and generalise aspects of the input into pre-established categories, creating information for more central processing (Basar, 1988). This would mean that the limit cycle represents a template, an image of the input that the animal is searching for or is expecting. Basar (1985a) suggests:

"We suggest that Freeman's concept can be generalised to various sensory systems and to EEG frequencies, such as delta, theta and alpha. Expectancy and selective attention associated with regular, frequent target stimuli result in highly synchronised EEG activity. This regular "limit cycle" activity occurs in various frequency ranges between 1 and 40 Hz. We conclude tentatively that the 1-4 Hz, 4-7 Hz, and 8-13 Hz activities serve as "operators" in the selective filtering of expected target stimuli." (Basar, 1985a:51)

Thus, Basar postulates that the frequency channels appear to be fundamental transmission channels in which " heterogeneous messages during sensory and cognitive processes occur " (Basar, 1985a: 52). Furthermore, he suggests that sensory and cognitive tasks use the same frequency channels but with different weights (Basar, 1985a).

It would appear in conclusion that the functional significance of the EEG is not agreed upon, and also it seems that different authors reach different conclusions depending on the type of research they are conducting. So, studies that are using the EEG as a measure of psychological state, physiological arousal or changes in these, related to tasks discuss the functional significance of the EEG only in terms of their remit. This leaves us with a number of studies demonstrating a change in the EEG related to some manipulation and the functional significance of the change, if this is discussed at all, is related only to the manipulation under study. Lorig & Schwartz (1989) summarises the problem:

"Unfortunately the relationship between these [cognitive processes and brain activity] processes remains elusive and it is confounded by simplistic theoretical formulations regarding the presence of certain forms of EEG and their location on the scalp. Much of the research on EEG during cognitive task performance has been driven by a localisation of function perspective and has attempted to determine the cortical area of greatest activity and then attribute function to that area." (Lorig & Schwartz, 1989: 369)

Then there are a number of studies that take a more holistic view of the EEG and discuss, as Basar (1988) and Freeman (above) have, the gross functional significance of the EEG.

The consensus of opinion seems to be that the EEG is a significant process in the transmission of information to and from areas of the cerebral cortex, although the exact nature of the process is not well understood, nor in many cases, is the EEG sufficiently well conceptualised. A similar and related problem relates to the automatic division by some imaging machines of the EEG signal into four or five main frequency components and the functional significance attributed to the separate wavebands. It appears that most researchers are agreed that the EEG is not "simple noise" but is in some way a memory-related and cognition and sensory - related operator that seem to govern the most important information transfers in the brain.

Odour processing and brain potentials

EEG studies

One of the earliest studies to use EEG as a method of looking at the processing of odours by the brain was carried out by Moncrieff (1962). He expected to find a disturbance of the alpha rhythm mainly because it seemed to be the dominant frequency in adults and nothing much was known about the other frequency wavebands. Moncrieff (1962: 757) suggested that they may be " the waste end-product of some cerebral processes, perhaps the smoke from smouldering biochemical fires." He used from five to eight electrodes, half placed on each side of the head and recorded the alpha rhythm of subjects smelling various pleasant and unpleasant odours. He did note some suppression of the alpha rhythm and the appearance of bursts of high frequency that occurred with the presentation of odours but these are highly unreliable results, as the testing system was far from ideal. Moncrieff can be seen as the crude beginnings of a field that still contains little published work compared to research in the other sensory modalities.

A continuing series of reports concerning the effects of odours on the EEG has been produced by Lorig and colleagues (Lorig, 1989; 1991; Lorig, Herman, & Schwartz, 1988; Lorig, Schwartz, Herman & Lane, 1988; Lorig & Schwartz, 1988a, 1988b; Lorig, Huffman, & De Martino, 1989; Lorig, Herman & Schwartz, 1990; Lorig, Herman, Schwartz & Cain, 1990; Lorig, Huffman, De Martino & DeMarco, 1991; Lorig & Roberts, 1991). Lorig has also been interested in the analysis of EEG data (Lorig, 1984, 1986; Lorig & Schwartz, 1989).

Lorig mostly used a time domain method of analysis on EEG data, to determine the amount of a particular frequency, typically alpha or theta, in chosen epochs. His early experiments seemed to suggest that the odours of spiced apple, eucalyptus and lavender could produce different patterns of EEG theta activity, using data from four electrode locations; F7,T5, F8, T6 (Lorig & Schwartz, 1988a)(see Appendix 2.4.1). A second experiment found that the effect of the spiced apple odour, a decrease in theta, may have

been produced by cognitive effects as the subjects imagined the food and not a change in CNS activity caused by the inhalation of the odour. Lorig suggests that to reduce the effects of cognition and the activation of memory perceptually similar odours must be used.

A further experiment using five floral note perfumes found significant effects in alpha and theta that produced different hemispheric patterns of activity (Lorig & Schwartz, 1988a). The results do not show a trend however and Lorig makes no attempt to account for the differing patterns, beyond reporting that alpha was more prominent in the posterior region, as would be expected (Nunez, 1981). Lorig suggests that these results indicate odours exert detectable effects on CNS activity and that they may achieve this by modulating limbic system activity demonstrated by the change in theta activity. Such a change in limbic system activity may result in an alteration in subjective mood state which Lorig found. It was noticed however, that even perceptually similar odours can produce very different patterns of hemispheric EEG activity and that the expectation of an odour in the no-odour control condition can affect the EEG and so doesn't provide a complete control condition.

It must be said that the early work of Lorig gave the field of EEG and odours a good start. Although improvements in methodology could be suggested, such as the use of more electrodes, these early experiments showed that with care the effects of odours on CNS activity could be reliably studied. However, the use of only four electrodes allows only a gross picture of EEG activity, and the link between such measures and the hypothesized limbic system modulation is speculative. Also, it is important to note that Lorig was studying the effects of an ambient odour because each of the epochs studied was 10 seconds long, taken from the EEG record of one minute's exposure. Thus, he is not studying odour perception but odour processing, at a later stage. Lorig himself notes that habituation to olfactory stimuli is rapid (Carlson, 1981 cited in Lorig et al 1988) which may explain why we rarely pay sustained attention to olfactory stimuli. However, he

neglects to mention that this may have affected his results in that the first epoch studied may well be expected to differ from the last, as the subjects' interest wandered.

Further experimentation (Lorig et al, 1988) demonstrated that during nose inhalation of room air, EEG alpha activity is reduced in the left hemisphere and beta activity shows greater spatial diversity, when compared to mouth inhalation of room air. Lorig suggests that this indicates that air entering through the nose contains more odour information than that entering through the mouth, and that undetected odours can greatly influence on-going CNS activity. Lorig is suggesting then that odours: both sub- and supra-threshold; and those perceptually similar as well as those perceptually dissimilar, affect the CNS in different ways and that the effects are more marked when air is breathed in through the nose, than through the mouth. What he fails to provide however, apart from a description of the results, is an interpretation.

Why is alpha reduced in the left hemisphere during nose inhalation? Why does beta show more spatial diversity during nose inhalation? Do these effects suggest that these frequencies constitute a monitoring process for inhaled air that has passed over the olfactory receptors? Little stimulation of the olfactory receptors occurs during mouth inhalations, so does this explain the lack of any significant change in activity? The differences that were found to occur in the inhalation versus the exhalation periods are reported but not accounted for. It may well be that these effects show the frequencies responsible for different levels of processing, the reduction in alpha in the left hemisphere, during the nose inhalation may be taken to confirm that the CNS has been aroused by the olfactory stimulus and the greater spatial diversity at this point in beta may suggest some information content being present in this frequency. The increase in theta in the right hemisphere during exhalation may represent this frequency's involvement in a re-setting mechanism, that takes the system to a different state after the inhalation phase and prepares it for new input.

Many of these points are speculative but it is noticeable that the published work that uses EEG to study olfactory processes, is hampered both by the lack of a conceptual

framework and the lack of a theory as to what the results of such studies may mean. It is interesting to read how the EEG may be affected by olfactory stimuli, but it is also necessary to provide some theoretical explanation, speculative or not, as to why these effects may occur. This is without doubt a very difficult proposition: the functional significance of the EEG itself is not well understood and to combine the difficulties associated with the collection and interpretation of such data with the difficulties associated with the testing of olfactory stimuli and the lack of demonstrated neocortical pathways mean that researchers in this area must be extra careful. It also means that they need to construct models of the olfactory processes and these must be allied to strictly controlled experimentation.

In a further paper Lorig (1989) does develop a model of odour processing but it is mainly a rough flow chart of information through the levels of the olfactory system. Lorig suggests that a spatial pattern appears in the olfactory bulb as a consequence of the inhalation of a novel odour, which is then stored as a template, which can be applied when an odour is presented (Skarda & Freeman, 1987). The expectation of an odour may then produce replicable, spatial patterns of bulbar activity. He suggests that after inhalation of the odour, multiple templates are applied until a match is found. His model is rather vague as to detail, especially past the level of the olfactory bulb. It is difficult to properly evaluate such a model as it makes no specific predictions, however, it represents a small first step.

Lorig does note that arousal and attention play a part in influencing the EEG during the perception of an odour, and that Freeman's work with the rabbit olfactory bulb may have consequences for human theories of odour perception, but still fails to suggest a strong functional role for EEG in the perception of odours. He emphasises that theta is known to decrease in the presence of sensory stimulation suggesting an increase in arousal. However, he notes that he and his co-workers found a decrease in arousal with the presence of a food odour and suggests that the cognitive mediation involved in imagining the food leads to feelings of relaxation. One factor that is not mentioned is, had the

subjects eaten recently before being tested. It seems likely that the odour of food will provoke different responses in hungry as opposed to satiated subjects. Thus, it is important to remember that cognitive effects will influence EEG in addition to any neurophysiological effects caused by inhalation of an odour.

Also, intriguing to Lorig (1989: 396) is the fact that humans display a remarkable lack of attention to olfactory stimulation and wonders " why [low concentration] odours go undetected" and postulates that an odour is only noticed when the stimulus is in disagreement with the bulbar template. This seems extremely plausible and his suggestion that unless there is the above discrepancy, odour information would be prevented from reaching the higher cortical structures that mediate awareness is convincing. However, again he fails to detail how this process may occur, despite the demonstrated presence of multiple feedback loops present in the olfactory system and their capacity at each level to engage in massive inhibition.

Lorig (1991) further investigated the hypothesis that odours exert powerful effects at a sub-cortical level. The methodology employed in this study is considerably more sophisticated than in his previous studies. In this first experiment, three concentrations of Galaxolide (a synthetic musk-like odour) were prepared, sub-threshold, approximate-threshold and supra-threshold. Nine electrode locations were used in this study (F7, T3, T5, Fz, Cz, Pz, T4, T6 (see Appendix 2.4.1)) and subjects breathed in each of the concentrations through a lightweight oxygen mask connected to an olfactometer. A further part of the experiment involved the subjects engaging in a visual search task in a no odour control and while exposed to the sub-threshold Galaxolide. Results indicated that EEG activity seemed related to the concentration level of Galaxolide but in a very inconsistent and not a statistically significant way. However, the no odour control condition differed significantly from the sub-threshold Galaxolide condition. Activity in alpha was reduced when the small level of Galaxolide was present, supporting Lorig's assertion that odours that the subject is not aware of can in fact affect the activity if the CNS.

Of further interest was the finding that the response latencies in the visual search task doubled in the presence of sub-threshold Galxolide and Lorig maintains that the odour even though not consciously perceived, interfered with the cognitive component of the task. A further study was designed to pursue this interpretation (Lorig et al 1991). By using an auditory odd-ball task and recording event- related potentials (ERP's, discussed fully below) Lorig was able to show that the amplitude of the P300 and the P200 increased during presentation of an odour. The P200 response changed even when subjects did not consciously perceive the odour. This again demonstrating that seemingly undetected odours can affect cognitive processing.

Event-related potential (ERP) studies

Although the topic of this thesis is concerned with the EEG and olfactory processes, it is important to note that related research is taking place concerned with the electrophysiology of odour perception. Two avenues of recent research will be presented here, the event-related potentials, and the contingent negative variation (CNV). Both of these areas have provided important clues as to what processes may take place in the olfactory system and the main findings will be discussed.

The ERP is a specific change in the on-going EEG resulting from the stimulation of a sensory pathway. Sensory evoked-potentials are time locked to the presentation of a stimulus and are specific to the sensory system stimulated. If these potentials are recorded from the scalp the signal is weak, typically considerably less than 50μv and it has to be filtered from the background activity of the brain using special computerised averaging procedures. Using such a procedure it is possible to let the randomly occurring fluctuations in the EEG record cancel each other out, leaving the averaged sensory evoked potential that displays the time course and waveform of the electrical events that occurred when the information was processed (Martin, 1985). Recording of auditory, visual and somatosensory evoked potentials have been commonplace since the advent of the new technology but a more difficult proposition has been to record olfactory evoked potentials. Because of the necessity of time locking the presentation of the stimulus,

positive and negative waves are often separated by a fraction of a second, the obvious difficulties with chemosensory stimuli become apparent.

Olfactory evoked potentials have been recorded however most noticeably by Kobal and Hummel (1991). They suggest a particular nomenclature for these potentials: olfactory evoked potentials (OEP's) for those substances not perceived by anosmics; chemosomatosensory evoked potentials (CSSEP's) for those potentials elicited by stimuli that involve no olfactory component; and chemosensory evoked potentials (CSEP's) as a general term for potentials elicited by chemical stimulation. A state of the art olfactometer is vital for the accurate presentation of the stimulus and to ensure sufficient activation of the receptor sheet.

If the time delay after the presentation of the stimulus is examined it becomes clear that several components combine to give early, intermediate, late and ultra-late phases of the potential (Kobal & Hummel, 1991). Also near field potentials and far-field potentials can be distinguished, depending on the distance from the generator and the recording electrode. To date only late near-field olfactory evoked potentials have been recorded in humans and the location of the cortical generators are unknown (Kobal & Hummel, 1991). The earliest component of an OEP appears at 150-200 msec after stimulus presentation. One of the most apparent characteristics of the ERP is its dependence on stimulus intensity and this has been demonstrated in both the CSSEP and the OEP.

One of the most interesting aspects of recent work has been the use of topographic mapping of the ERP. Kobal & Hummel (1991) have observed correlates of olfactory induced "emotions"and CSEP's. They discovered that the P2 latencies are longer when the left nostril is stimulated with a pleasant odour, and the right nostril is stimulated with an unpleasant odour. Thus the hedonics of an odour can affect the ERP, and it may be that these results reflect the way in which the two hemispheres process emotion, the left hemisphere being predominantly involved with pleasant responses and the right hemisphere processing negative emotions (Ahern & Schwartz, 1985). As yet there is no

suggested mechanism for this effect. The implications of hemispheric processing differences for the interpretation of the EEG is discussed in a further section.

Another method of classifying ERP's is by the information postulated to be coded in them:

"Exogenous ERP's, are determined by the characteristics of the afferent input and hence the eliciting stimulus. In contrast the endogenous ERP's vary with the state of the subject, the meaning of the stimulus, and/or the demand of the task related to the respective stimulus." (Kobal & Hummel, 1991:272)

The human P300 has been extensively studied and is usually elicited by rare or omitted stimuli in a series of expected stimuli. It seems to be associated with sequential information processing, short-term memory and/or decision making (Buchwald, 1990). It has been found that in olfaction this late positive component did not reveal a hemispheric nor an hedonic interaction, which indicates that the latency effect related to the hedonic dimension of an olfactory stimulus must occur subcortically, because it is demonstrated at P100. Thus, there are obvious benefits in studying olfaction in this way but it must be said that a great deal of work remains to be done in this area before a set of consistent, interpretable results is achieved. Work by Petsche & Rappelsberger (1991) suggest several reasons for dissatisfaction with the ERP work and results from P300 studies, suggesting that the shape of the ERP is only a minimal aspect of the electrical spatio-temporal continuum and therefore is unlikely to shed light on global higher cognitive functioning. Also, they maintain that paradigms having a laboratory nature are fairly unlikely to shed light on daily thinking or tasks. Furthermore, the relationship between the ERP and EEG is not yet well understood and so it is difficult to suggest what bearing ERP results may have on any interpretation of EEG data.

Furthermore, when conducting ERP studies on olfaction it is impossible to allow the naturalistic sniff to occur. Presentation of the odours must be by olfactometer and be time locked. To what extent this may affect the validity of the olfactory ERP is not yet known,

but the work of Freeman (Skarda & Freeman, 1987) suggests that the inhalation cycle is an important part of the olfactory process, allowing the olfactory system to reset in anticipation of the next presentation. For the purposes of this study it was considered important to have as naturalistic a setting as possible, and so an olfactometer was not used.

Contingent negative variation (CNV) studies

The Contingent Negative Variation (CNV) is a slow upward shift (a negative potential) in brain response that occurs when subjects' are expecting something to happen or in the anticipation of motor activity. This slow potential has been studied extensively and is reported elsewhere (Rebert, 1980). This section will concentrate on the effects of odour on the CNV. The early portion of the wave, the "O wave", is related to orientation to the warning stimulus, and predominates in frontal electrodes. The later "E wave" is prominent in the central and parietal areas and is the later component of the wave. This arises because the frontal regions of the brain have a role in the attentional processes, and the shift to the parietal areas occurs because of the location of the motor cortex. The CNV can be correlated with psychological variables but is not visible within a single EEG recording and only appears after the EEG traces for a number of trials have been averaged (Torii, Kanemoto, Miyanchi, Hamauzu & Kawasaki, 1988). The known psychological factors that affect the CNV include, attention, expectancy, thought, and instruction set: others, such as: levels of consciousness; anxiety; and stress, are also known to have an effect (Torii et al, 1988; Lorig & Roberts, 1990).

Torii and colleagues (1988) used the CNV as a method of investigating the sedative or arousing effects of some odours. Their results showed that jasmine which is thought to be stimulating did increase CNV amplitude. The CNV decreased in response to lavender, generally thought to be relaxing, confirming anecdotal evidence related to these odours. Lorig & Roberts (1990) suggest that instead of showing a direct effect of odours on the arousal level of the CNS, the results may be explained in terms of cognitive mediation as they have demonstrated is the case in other studies described above.

In an imaginative experimental paradigm Lorig (Lorig & Roberts, 1990) tried to replicate the findings of Torii. Further, he misled subjects about the odours they received in order that the expectations of the subjects' could be separated from the direct physiological effects of the presented odour. Replication of Torii's results was achieved an indication that the CNV is a valid measurement for electrophysiological events involved in odour perception. Furthermore, he demonstrated that when subjects were presented with an identical mixture of odorants, but were primed to expect differences, the CNV differed in terms of their expectations. Lorig concludes:

"It is quite probable that odors exert EEG effects in three ways: (1) direct physiological alteration of the CNS; (2) changes in the CNS due to cognitive mediation such as previous associations or mood induction, and (3) possible pharmacological alteration of CNS activity through prolonged exposure to odor chemicals." (Lorig & Roberts, 1990: 544)

Thus it is clear that EEG, the ERP and the CNV are viable and productive methods for studying the effects of odours on the CNS, and the next section considers the use of an alternative methodology.

Topographic mapping studies

Studies using topographic mapping to study the EEG response to an odour are rare, as the technology has not been available for long and its application to the study of olfaction has not been widespread. This is because of the expense of the necessary equipment and the scarcity of researchers in this area. Some pioneers however have recently made advances in this area (Van Toller, 1988; Kendal-Reed, 1990; Van Toller, Kendal-Reed, Sleight & Behan 1986-7; Van Toller & Kendal-Reed, 1989; Van Toller, Hotson & Kendal-Reed, 1992).

One of the early studies involved the topographical mapping of olfactory evoked potentials (Van Toller, Hummel & Kobal, 1986 cited in Van Toller & Dodd, 1988; Kobal, Hummel & Van Toller, 1992). This study aimed to examine the topographical distribution of brain activity in response to four stimulants: hydrogen sulphide, vanilla, carbon dioxide and menthol. The latter two stimulants are primarily trigeminal which means that they impinge on the trigeminal or fifth cranial nerve that innervates the nasal passages and whole facial area. Hydrogen sulphide and vanilla are primarily olfactory and impinge onto the olfactory or first cranial nerve that innervates the olfactory epithelium. Eight electrodes were used and referenced to one earlobe. The results showed that subjects could indicate which nostril was being stimulated when the trigeminal stimulants were used, but not when the olfactory stimulants were used. In addition, the topographical distribution differed depending on the type of stimulus being presented, although not in a consistent manner. The authors suggest that olfactory and trigeminal responses are mediated by different neuronal populations. The results did show that topographical mapping can be a useful tool for studying responses to odours, albeit using EP's.

Using B.E.A.M, Van Toller, Kendal-Reed & Sleight (1986-7) were able to demonstrate qualitatively that EEG is able to capture topographical changes associated with the inhalation of different odorants. This technique uses 28 electrodes and so allows a good

coverage of the cortical surface under the scalp. The EEG signal is decomposed by Fast Fourier Transform into the five classical wavebands. Appendix 4 gives details of this technique, as the work completed for this thesis was carried out with the same machine.

The above research provided the impetus for further work of a more detailed nature. It became obvious at this point to Van Toller, that a more systematic approach to the study of EEG responses to an odour was necessary. To this end a series of research projects was begun to investigate more thoroughly what odours cause what kind of topographical distribution. The present thesis forms part of the continuing programme to investigate this area. The particular research aims and hypotheses of this study are given in Chapter 4. This section will review the methodology used so far in these studies and the results achieved.

In the original methodology, subjects were tested in a large, well ventilated laboratory, comfortably seated and had reduced auditory and visual input. This perceptual isolation was achieved by the use of goggles and headphones. Subjects wore a fabric headcap that contains 28 electrodes in a modification of the International 10/20 system of electrode placement, referenced to linked earlobes. The odours were iso-intense and covered a range of odour types and hedonic tones, and were usually presented on perfumers' smelling strips. Subjects were asked to breathe in through their nose and out through their mouth to prevent retro-nasal stimulation of the olfactory receptor sheet.

A qualitative assessment of the topographical maps led the authors to examine only the alpha frequency as it appeared to show the most dramatic changes. The first epoch after the presentation of the odour was chosen for analysis as it was expected to show the effect of the inhalation of the different odours. The chosen method of analysis was multidimensional scaling (MDS) and an analysis of variance (ANOVA). An MDS plot was produced to show the positionings of the odours in terms of alpha responses, scores close together on the plot being more similar than those further apart. There were found to be seven electrodes that gave rise to alpha responses that would best account for the MDS map of the odours, using a vector correlation procedure. These electrodes were

CP1, PZ, CP2, C4, TCP2, and O1, and OZ (see Appendix 2.4.1) which are located in the parietal and occipital areas. Psychometric scores were used to construct a further MDS map based on similarity, on which it was possible to correlate the amplitude values. The psychometric dimensions were: pleasant/unpleasant; strong/weak, and familiar/unfamiliar. Four electrodes, FZ, T3, FTC1 and F4 gave a significant correlation.

An ANOVA of individual subject data was also carried out, using all of the electrodes identified above. The results showed a trend for electrode x odour in alpha. The authors suggest that the first group of electrodes identified in the parietal and occipital areas may be "sensory" in nature. The more frontal electrode group is not associated with a particular psychometric dimension but instead the power of the electrical response increased as the intensity of the psychometric response increased, whatever the dimension.

A further study using the B.E.A.M was carried out using twelve week old infants, involving specially adapted electrode headcaps. This study (Kendal-Reed, 1990) examined the delta frequency EEG responses in seven babies to a range of food odours. Kendal-Reed examined a set of 10 electrodes located in the parietal/occipital region identified in the above study and submitted the data to a univariate repeated ANOVA. His results must be interpreted with caution in relation to the present study considering that the seven subjects' were babies, he examined only the delta waveband and he only considered posterior electrodes. His results suggest that there is some noticeable EEG response to odours but this could not be related to odour type.

More recently a report by Klemm, Lutes, Hendrix & Warrenburg (1992) examined EEG in response to various odours. Nineteen electrodes referenced to linked earlobes were used and the EEG signal was split into the four main frequency bands. Eight seconds of "representative" and artifact free EEG were selected for FFT before odour presentation, at three points during odour presentation, and 30 seconds after odour presentation. The 16 subjects were all female. The odours used, seven in all, (birch tar, galbanium, heliotropine, jasmine, lavender, lemon and peppermint) were presented to the subjects for

psychometric rating before the EEG testing. The collected data was presented in the form of average topographical maps for each subject. A grand average was also computed. For further analysis, the data was normalised and a univariate repeated measures ANOVA was carried out with the Greenhouse-Geisser adjustment (discussed in Chapter 4). The authors found that the psychometric responses carried so little variance that a correlation with EEG responses was not possible.

Their discussion of the "analysis" of the topographical maps is inadequate. They lined up examples of maps for each subject at each stage of the trial and concluded that:

"Subjects differed from each other in their response to odors, and this was quite apparent from inspection of the maps. During odor stimulation, hemispheric asymmetries and regionally specific changes were quite evident. ...Although the average maps show clear differences, the individual variability in the data made it difficult to demonstrate statistically significant differences across the whole subject group. As mentioned, not all subjects responded the same way to every odor. Moreover, the response did not always occur in the same stimulus epochs." (Klemm et al, 1992: 352)

The authors note that they are looking at average maps but fail to mention that these maps may be highly misleading and their conclusions amount to nothing useful. All researchers in EEG realise the high level of individual variability and the dangers of averaging all the data just to make the analysis more simple. The authors also note that the response to the presented odour occurs at different times during presentation, and it is not at all clear that they are witnessing odour related changes, they merely assume that they are. A visual analysis of the topographical maps alone is not really a reportable result, it should be a prelude to further analysis.

Their statistical testing is also suspect. For the ANOVA's, data from three or four electrodes were collapsed to form five regions. Why this was done is not clear. They begin the article with a statement about the need to use as many electrodes as possible because of the lack of demonstrated neocortical representation of odour perception, but

then proceed to collapse all the data into five regions. They do realise that their demonstrated significant effects "should perhaps be considered mainly as descriptive of effect size" and that "results should be replicated in a design more amenable to statistical design"(Klemm et al, 1992: 353). Their results contained a hint of the involvement of theta in mediating odour response. They go so far as to suggest that:

"The response in the posterior region might have been expected because those electrodes are positioned more closely to olfactory cortex (piriform and entorhinal). Perhaps the responses occurred because subjects were visualising object or scene memories that odors evoked." (Klemm et al, 1992 :356)

This kind of speculation is obviously borne of the authors lack of expertise in EEG. No-one can suggest seriously that it is possible to speculate about generator sources for observed scalp activity from such data. Nor do the authors mention why they consider that these effects were because of imagery influences. Their review of previous literature on this topic is deliberately blinkered and sparse with many ideas seemingly thrown in for good measure.

In conclusion, this report shows what can happen if researchers are able to utilise an imaging machine but lack the necessary EEG expertise or fail to consider the complex and various factors that contribute to an EEG record. If this area is to achieve a valid progression, then the neurophysiological basis of the effect of odours on the EEG must be considered, models should be developed and tested and it should not be sufficient to note merely a change in EEG, upon the presentation of an odour. A multidisciplinary approach is vital. The EEG is a highly variable and dynamic phenomenon that is constantly changing and shifting within certain parameters, which makes any changes related to a stimulus, difficult to characterise and compare. The need for multivariate time series analysis techniques is now vital. The aim of research in this area, demonstrated by Lorig and Van Toller, is to find reliable and replicable changes related to some aspect of the odour, either its physical properties, its perceived qualities or its

associations. This is an extremely complex task and one that cannot be simplified. These issues are discussed further in the last chapter of this thesis.

Evaluation of previous studies

It is clear that the studies presented so far do not form a body of established findings, but rather provide many, as yet unconnected (by a functional explanation) clues, as to the processes involved in the brain's response to odours. There are several reason why it would be unwise to compare and contrast the studies so far carried out, without a great amount of caution. The studies use different reference electrodes, a different number of electrodes, different methods of data analysis and different stimuli. Some studies use FFT whereas some studies use the raw EEG signal. It is impossible to compare at this stage the relationship and implications of the ERP and the EEG studies. All that can be concluded is that odours do affect the CNS and that these changes can be captured by EEG. This study aims to extend and quantify the previous findings, using strict methodology and valid analysis procedures.

CHAPTER THREE

Recent developments in neural network theory and Chaos theory relevant to odour processing: Introduction

"Studies of formal networks composed of binary-valued information processing units, highly abstracted versions of biological neurons, either by mathematical analysis or by computer simulation, have emerged as a third route [after physiology and philosophy] towards a better understanding of the brain, and possibly of the human mind." (Muller & Reinhardt, 1990)

"The olfactory pathway is thus a prime target for simulation by a new generation of more realistic neural networks. This will contribute toward a definitive understanding of the nature of olfactory processing. It should also lead to the development of devices, with practical applications in many fields of scientific and industrial interest, for detection, discrimination, analysis and representation of molecular information." (Shepherd, 1991: 32)

Recent advances in neural network theory and the blossoming of Chaos theory in mathematics, together with the meticulous research of Freeman (1987, 1991b) have led to the development of a dynamic model of the olfactory bulb and new ways of viewing, interpreting and analysing information obtained by olfactory experiments. The suitability of the olfactory system for studying neural substrates for learned pattern recognition, (Haberly & Bower, 1989) together with the incorporation of certain chaotic features in a dynamic model of the olfactory system, mean that olfaction is at last receiving long overdue attention. Furthermore, such developments are important for this thesis, in that they try to elucidate the processing and coding that takes place in the olfactory system. Such knowledge needs to be based on a thorough understanding of what the system has to achieve, and valid anatomical and physiological data. The new mathematics of Chaos has two very important implications for this thesis. First, it provides a new conceptual framework with which to view the olfactory system, as regards the type of processing that

is assumed to be occurring at bulb and pyriform cortex level. Secondly, it has great implications for the analysis and interpretation of EEG data.

As we can see from the previous chapters, there have been great advances in explaining the physiological and biochemical underpinning's of how the central nervous system in general, and the olfactory system in particular, processes relevant environmental information. Recent contributions from mathematicians and engineers in building advanced pattern recognition devices, have culminated in a revival of connectionism and the arrival of "neural networks."

Muller & Reinhardt (1990) also note that this recent upsurge of attention on neural networks has come about not to model the brain, but because of their potential to provide solutions to the technical problems surrounding "artificial intelligence" that the traditional logic-based approaches have so far failed to provide. Many authors (Amit, 1989; Erdi, 1991; Muller & Reinhardt, 1990) caution that many of the claims made for the virtues of neural networks are exaggerated and that even the most successful applications, concerned with content-addressable memory and pattern recognition, have led to relatively little being learned.

Cognitive scientists have for many years made explicit or implicit use of computer analogies in their work, trying to identify the processes and mechanisms that underlie human cognition. In the early days of artificial intelligence (AI) there were several attempts to write computer programmes that enabled the computer to perform tasks that mimicked the behaviour of subjects. The products of AI, known as expert systems, had some success in medical diagnosis for example (Muller & Reinhardt, 1990). However, they were too slow to perform the pattern analysis necessary on a piece of speech. The real reason for the foundering of the AI approach has been its use of formal logic reasoning, which means that the logical structure of the problem under study has to be analysed beforehand, plus the limitations of sequential processing.

In the field of mathematics, "Chaos" theory has revolutionised the way in which the world is conceptualised. Chaos has been "discovered" in mathematical systems, in natural systems such as the weather, and in biological systems such as ourselves. All of these points will be elaborated in the following sections. Taken together, these developments have provided researchers, with the tools necessary to model the often unpredictable behaviour occurring in biological systems. The aim of this chapter is to show the contribution that these developments can make to modeling the olfactory system.

There are a number of requirements for any theory which seeks to explain how a system interacts with a complex environment in an adaptive way. The theory must be action-oriented, must be able to integrate sensory information, action and update any internal models. The organisation must be hierarchical, with the potential for feedback and feedforward (Szentagothai & Arbib, 1975). The emphasis on hierarchy arises because it has been a tenet of the classical view of forebrain organisation that the perceptual processing of sensations is performed in such a fashion (Amit, 1989). Such an approach allows neural systems to be studied at the molecular, membrane, cellular, synaptic and system levels. Similarly, mathematical models of dynamic systems can be at the single- and multi-level (Erdi, 1991). Also, neural nets seem best suited to approaching problems in sequential steps of increasing detail, i.e., in a hierarchical way which allows them to classify and generalise. Traditional methods of AI are constrained by classification and generalisation rules.

Neural networks and connectionism

Recently there has been an interest in the development of models and artificial devices that mimic the supposed operation of the central nervous system, albeit in a remarkably crude fashion. Such devices and models are able to recognise and associate complex patterns, by the action of large numbers of highly interconnected, relatively simple processing elements. Nervous systems can be characterised in a similar fashion as strongly connected networks of cellular units, i.e., neurons (Labos, 1987). Because of

this similarity between the models and some general properties of the CNS they have come to be known as neural networks (Haberly & Bower, 1989). These networks process information in a parallel, rather than a serial fashion, as is found in conventional digital computers. Connectionist models involve parallel distributed processing, which involves a dense interconnection of processing units that interact with one another by sending and receiving signals. The signals are modulated by weights that are associated with the connections between the units. Processing is distributed throughout the system and units are usually arranged in interconnecting layers (Skarda & Freeman, 1987).

The advantages of conceptualizing neural behaviour in this way are many. The network is able to perform associative functions such as: pattern completion from degraded input; novel input patterns eliciting related outputs; linking previously unrelated patterns. Memories are stored in a distributed fashion, accross the processing array, and individual connections participate in the storage of the many patterns (Haberley & Bower, 1989). The design of some networks allows the self-organisation of behaviour. Local factors influence the strength of connections between processing elements, allowing the network to develop its own internal representation of stored information. This is termed content-addressable memory and is in direct contrast to location-addressable memory, used by digital computers (Norris, 1991).

The development of a simple two layer neural net involves training the network on known sets of input and output patterns. A target output pattern is given to the network, which it has to achieve given a certain input pattern. This it does by calculating the error from the previous layer. More complex models, such as three layered networks, require techniques such as back-propagation. Stated very simply, in multi-layered models the input and output elements are connected via one or more "hidden units" which can form internal representations of the data and thus solve more complex problems. The network first establishes interconnections at random, then adjusts the weights accordingly to calculate a new output pattern, comparing this to the target output and so on.

One problem associated with such networks is the possibility that they can never solve the problem if they are unable to find a suitable set of weights: they are caught in a local minimum which implies only a partial solution (Norris, 1991). Another problem concerns generalisation. Ultimately the networks must be designed so that they can induce rules, and so generalise their knowledge to previously un-encountered inputs and behave appropriately. One way that they may achieve this is by introducing features such as chaotic activity. The advantages and justifications for the introduction of non-linear dynamics into models of neural nets will be fully considered after some general comments regarding Chaos theory.

Chaos theory - General

This sub-section details the events occurring between two definitions of chaos. The first and oldest definition is: Chaos - 1. "utter confusion or disorder." 2. "formless primordial matter." (Hawkins, 1991) One of the most recent definitions is: Chaos - 1. "lawless behaviour governed entirely by law." (Stewart, 1989) Recent publications in this area (Gleick, 1988; Stewart, 1989) are accessible texts on this subject and what is given below is a selective and condensed summary of the ideas contained in both.

The discovery of Chaos has created a new paradigm for scientific modelling. That simple deterministic systems can create extraordinarily complex and random behaviour, is a hallmark of Chaos (Crutchfield, Farmer, Packard & Shaw, 1986). There is also the paradox that such behaviour is ruled by fixed laws and is deterministic. Small uncertainties in a dynamic system are amplified by stretching and folding behaviour, which ensures that the microscopic effects soon affect macroscopic behaviour. It is this behaviour that has come to be known as Chaos.

The view of scientists in the 17th and the 18th century was that nature had laws and that they could be found. If they hadn't been found so far this was because the laws were still waiting to be discovered or because the system under examination was very complex. The paradigm that gradually emerged was that the way to model nature is through a

system of differential equations. Probability theory gave the mathematicians new tools to work with and by the end of the 19th century, science had two paradigms for mathematical modelling. Differential equations for simple systems and statistics for more complex systems. The invention of topology by Poincare in 1887, was a landmark in the history of Chaos theory. He provided a new way of looking at dynamical behaviour, but was perplexed to discover the complexity that could arise from the simplest of systems.

The dynamical behaviour of a simple system, such as a pendulum, can be modelled more effectively by using geometry than a system of differential equations, but precise time dependence is lost. However, to solve the equations in a classical manner the equation must be "linearized" by throwing out all the awkward terms. It was assumed that because the neglected terms were small their effect would also be small. However, Edward Lorenz in 1963 had already shown with his now famous 'Butterfly Effect' that very small changes to a system, such as the weather, can have very large effects. The stretching and folding that occurs in even the simplest of dynamical systems can render their long term behaviour completely unpredictable. In 1977 Chaos became a fact, not a theory. The language of fractals provided by Mandelbrot was perfectly placed to describe the new mathematics. Since then Chaos is being discovered everywhere, not least in the natural world.

The basic idea to grasp in thinking about Chaos theory, is that the behaviour of a dynamical system can be visualised in state space. The notion of "state," the essential information about the system, is combined with notions of a "dynamic," a rule that describes how the state evolves in time. This evolution can then be visualised in a state space, an abstract construct whose coordinates correspond to the components that make up the state. Thus, it is possible to reinterpret a time series as a geometrical object. Often when mapping out the behaviour of a system it becomes clear that it is "attracted" to a portion of the state space. There are three basic types of attractor: a point attractor (best characterised by the behaviour of a normal pendulum); a limit cycle attractor (a pendulum

clock), and a torus which corresponds to quasi-periodic motion. Attractors are the geometric forms that characterise the long term behaviour of a system in state space. The set of points that evolves to a particular attractor, and a system may have more than one attractor, is known as its "basin of attraction."

Previous generations of scientists have assumed that unpredictability or "chaos" in the sense of utter confusion and disorder is generally a bad thing. Biological systems were assumed to require stable periodic behaviour. Recent work on the chaotic dynamics of the heart muscle suggests this view may be outdated, or at the very least, in need of serious re-formulation (Goldberger, Rigney & West, 1990). May (1987) has demonstrated the presence of chaotic dynamics in animal population biology over a number of years, and has provided a brief survey of the non-linearities and complex behaviour demonstrated by simple ecological and epidemiological models. The concept of dynamical diseases has been introduced and extended by Mackey & Milton (1987). In general it may be that for all oscillatory processes in physical systems, a regular and stable cycle is maladaptive. By introducing Chaos, a useful "wobble" can feature in the system, so that the overall behaviour can withstand occasional perturbations and remain stable. Unlike mathematical or chemical systems, however, biological responses are often short-lived. This causes problems in chaotic analysis as it proves difficult to characterise the attractor (Mpitsos, 1989).

The fact that Chaos exists in biological systems is no longer disputed and what occupies researchers is the necessity to characterise, explain, analyse and interpret their findings. The connection between Chaos and neural network theory is important because it may allow for more realistic modelling of actual behaviour, based on more realistic foundations of how neurons and groups of neurons process information.

Chaos and neural networks

The question "why the incorporation of Chaos into neural networks ?" can be legitimately be asked at this point. For this thesis it is something of a unifying principle. Freeman, has modelled the olfactory system using principles derived from Chaos theory. His system is based on valid physiological principles and examines the EEG from the olfactory bulb of rabbits. Chaos theory provides not only a new way to conceptualise the behaviour of neural masses, but also a method for analysing EEG data. This thesis suggests that the same conceptual framework may apply to the human olfactory system. Dvorak, Albrecht & Holden (1991) note that:

"We know a great deal about the electrical and biochemical processes taking place within some components of the brain, we can register signals that reflect the global activity of the brain with surprising accuracy, and we can assess, by psychometric methods, the overall performance of the brain. However, we still lack a deep understanding of the very basic principles of how separate processes in the brain are organised into the unified and coherent functioning that is characteristic of the brain." (Dvorak, Albrecht & Holden, 1991:3)

The authors go on to describe the application of mathematics to the study of brain processes, using the EEG as a particular example of the success that can be achieved using the new mathematical tools.

The incredible complexity of the brain at many levels has so far militated against any attempt to build a mathematical model of the dynamical structure of the brain that leads to a theory of brain functioning. However, the increased popularity of neural networks may provide a start in this direction. Such an arrangement of "neuron like" units can produce dynamics or behaviour similar to those recorded from actual brains. At the same time the introduction of nonlinear dynamics into such a network can produce a crude model of the chaotic processes that may be taking place in the nervous system.

The application of nonlinear dynamics to neural nets can be seen as almost inevitable. Since the findings of Freeman (1987, 1989, 1991b) suggesting that Chaos may aid the production of organised neural activity it seems sensible to introduce such behaviour into a system that models neural tissue. Also, the mathematical tools for the incorporation of Chaos into neural nets have only recently developed. To a large extent the application of nonlinear dynamics to neural nets has its origin in the analysis of EEG data. Such data has been shown many times to exhibit chaotic activity (Babloyantz, 1989; Babloyantz & Callez, 1991) and researchers have constructed model neural nets that display typical EEG output behaviour and they suggest that the human EEG is a result of similar mechanisms (Babloyantz & Callez, 1991). Perhaps the most important concept in Chaos theory is self-organisation, which refers to the search for general rules of emergent behaviour in complex systems:

"Our evidence suggests that the controlled chaos of the brain is more than an accidental by-product. Indeed it may be the chief property that makes the brain different from an artificial intelligence machine. One profound advantage chaos may confer on the brain is that chaotic systems continually produce novel activity patterns. We propose that such patterns are crucial to the development of nerve cell assemblies that differ from established assemblies. More generally, the ability to create activity patterns may underlie the brain's ability to generate insight and the "trials" of trial and error problem solving." (Freeman, 1991b: 41)

Moreover, the convergence of empirical data from neurobiology and the approaches from dynamical systems theory would appear to have provided the impetus for a new period of neural modelling that encompasses such notions as:

"..self-organisation..macroscopic order and disorder, pattern formation and pattern recognition, dissapative structures, synergetic systems, emergence of complexity, spatial coherence, order through fluctuations, noise induced transitions. Rhythmicity, considered as a paradigmatic illustration of self-organised temporal behaviour, is characteristic of the nervous system...The essence of neural organisation is- at its very

basis and its ultimate origin - self-organisation of spontaneous neural noise into spatio-temporal patterns of activity." (Erdi, 1991: 31-32)

Many researchers are now trying to integrate the properties of Chaos into such networks. Skarda & Freeman (1987) suggest ways that, in their view, most of the present parallel distributed processing connectionist models could be improved. It has already been shown in Chapter 1, that neurons in the olfactory system are subject to feedback, feedforward and inhibition. Some connectionist models of nervous system processing have incorporated aspects of these processes. However, the temporal and spatial processes occurring in the brain, long delays, temporal dispersions and spatial divergences do not occur in local feedback. For example, feedback between layers, such as the olfactory bulb and the pyriform cortex is not the same character as the short latency focused feedback taking place in the neuropil (Skarda & Freeman, 1987). At this time the author is not aware of any connectionist model of olfaction that takes such factors into account, and without such features it is doubtful the global behaviours of the neural dynamics can be reproduced.

Further on in this section the work of Freeman (1987), and his model of the activity occurring in the olfactory bulb of rabbits, in response to learned and unlearned odours, will be discussed. This will show clearly what important aspects of behaviour need to be adequately explained and accounted for by any neural network model, and how using the techniques of chaotic dynamics, can further enhance the model. Although pattern completion and recognition abilities of neural nets have been one of their most emphasised features, Skarda & Freeman (1987) suggest that this is inappropriate when looking at generated olfactory bulb activity:

"The neural system we have described is not best thought of as a pattern completion device, although it may do that. The problem is epistemological; we do not know what a completed pattern is (so convergence to it cannot be ascertained as in an error correction device), nor we suspect does the brain. We postulate that the nerve cell assembly (NCA) is activated wholly by input to any of its neural members,but we have no

measure or observation of what the NCA looks like or how completely it is activated. The output of the system does not consist of the "completed" pattern of the NCA but of the entire bulb governed by an attractor. Most generally these patterns are generated from within. Whatever "meaning" they have is embedded in the self-organised matrix of the entire brain." (Skarda & Freeman, 1987: 172)

Freeman (1987) also maintains that the word "pattern" is misleading and meaningless when considered in a chaotic, dynamic information processing system. In neural nets the target pattern can be achieved by presenting the optimal input prior to training to adjust the weights amongst the units. In living animals the 'optimal' presentation cannot be depended upon, either in the first or any instance to be compared to subsequent input. Freeman suggests that the animal's nerve cell assemblies are continually "destabilised" by information impinging on the senses, and so behaviour is in a state of continual re-adjustment. Freeman notes:

"In an alert, motivated animal, input destabilises the system, leading to further destabilisation and a bifurcation to a new form of patterned activity. Convergence to an attractor in one system (e.g., the olfactory bulb) in turn destabilises other systems (e.g., the motor system) leading to further state changes and ultimately to manipulation of and action within the environment." (Skarda & Freeman, 1987: 172)

A further consideration for the designers of connectionist models of neural activity is to place constraints and demands on the system akin to those placed on humans and animals by their environment. Animals and humans act via a sensory motor loop, which allows them to react, adapt, survive and reproduce. Incoming sensory information has adaptive behavioural consequences. No model yet devised, incorporates all of the above, especially not the last requirement for adaptive survival which will be the most difficult to attain in a non-biological system. In future all model builders will need to consider these points, if they are to devise a valid model of neural, and ultimately, animal behaviour.

Because of their long term unpredictability it is difficult to envisage such chaotic signals as information sources. Recent work by Mpitsos (1989) has concentrated on the ability of a very simple network to process a flow of chaotic information. Intriguingly the results demonstrated that the network could distinguish one chaotic signal from another and the network learned the fundamental qualities of the input which it could generalise to other signals. Further still, the network could accomplish this without adjustments of the weights.

Carpenter & Grossberg (1987) however would take issue with the idea that Chaos is *necessary* for a network to function in the manner suggested by Skarda & Freeman (1987) above. They have introduced the concept of adaptive resonance theory (ART) which they suggests is capable of: self-organising; self stabilising, and self-scaling its recognition codes in response to arbitrary input patterns (Carpenter & Grossberg, 1987). ART systems display several properties that fulfil the requirements of adaptive, dynamical systems. Any dynamical system, such as a neural network must be "plastic" enough to learn about significant new events that occur in its environment, yet be able to balance this against inputs that are unimportant or commonplace. Familiar objects must also be recognised quickly. This demonstrates that as yet the case for Chaos theory to be incorporated into neural network models has not been conclusively proved but the evidence gathered and considered so far suggests that the weight of evidence favours its inclusion.

Amit (1989) suggests that any theory of neural networks is to produce *exceptional* input-output relations, in that they should correspond to our intuitions about cognitive processes and our knowledge of neural organisation. He provides a list of attractive features which may be captured by a neural net model. While reading through the list it is difficult after reading the previous discussions of this thesis on Chaos theory, to ignore the potential that it may provide in satisfying these features:

"(1) biological plausibility ...(2) associativity is the impression that many similar inputs are basically collapsed on a prototype for purposes of cognition and manipulation...(3)

parallel processing is the articulation of tension between the slow basic cycle-time of neuronal processes and the impressive speed with which the system as a whole reacts to tasks ...(4) emergent behaviour....(5) freedom from homunculi ....(6) potential for abstraction." (Amit, 1989: 7)

Dvorak, Albrecht & Holden however have no doubts as to the importance of nonlinear dynamical systems theory:

"The brain will thus translate itself into its mathematical language." (Dvorak, Albrecht & Holden, 1991: 8)

Chaos, neural nets and odour processing

Several authors have now provided neural network models of olfaction. They have discussed how a network may process olfactory information and have explained certain olfactory phenomena, such as sensitivity enhancement, adaptation, and cross adaptation (Getz, 1991; Kauer, 1991; Li, 1991; Clarke, Chen & Kurten, 1989; Haberley & Bower, 1989). Freeman and his colleagues however, have concentrated on identifying the neural mechanisms responsible for the learning and subsequent recognition of odours. They have now, using the language of neurophysiology, statistics and non-linear dynamical theory, produced a model, using the rabbit olfactory bulb, that describes the neural dynamics responsible for recognition and discrimination. What follows is a summary of that theory (Freeman, 1991b; Skarda & Freeman, 1987).

The starting point of the theory is to ask questions about the brain's ability to discriminate between odours, and how the brain is able to recognise that signals conveyed from different receptors refer to the same stimulus. It is important to note first that every neuron in the olfactory bulb participates in generating a response to an olfactory stimulus, and so the relevant information is distributed bulbwide. In order to gather EEG recordings, a 60x64 electrode array was chronically implanted on the surface of the olfactory bulb of rabbits. Each electrode gave a mean excitatory response for a small

group of neurons located underneath while the rabbits were trained to lick or chew in response to different odorants, using standard reinforcement techniques.

When the animals inhale a familiar odour, a burst of EEG activity takes place, until exhalation. Such bursts oscillate at about 40 Hz, ranging from 20-90 Hz (gamma waves). In each set of these burst recordings Freeman was able to identify what he terms a "carrier wave" of activity. Each animal had its own distinctive EEG response pattern. The shape of the wave does not carry the essential information (in fact it changes each time the animal sniffs, even if the same odour is presented). This is carried by the distribution of carrier wave amplitude over the bulb. At receptor level, Freeman postulates that a nerve cell assembly (NCA), similar to cell ensembles described by Hebb, forms upon the repeated presentation of an odorant during reinforcement training. Thus, when any part of this assembly is activated, so are the reinforced synapses which send a distinct message to the bulb which then sends its message to the olfactory cortex.

Two factors affect the sensitivity of the bulb to odours. General arousal primes the bulb to receive input, for instance when an animal is hungry, or thirsty. The second factor is input itself. Freeman discovered an increase in gain (sensitivity of postsynaptic cells to further excitatory input) with excitation. As we have seen earlier, this discovery is important because neural network models assume that neurons are an maximum gain when they are at rest, and that both inhibition and excitation decrease gain so that the network remains stable. Similar events to those in the bulb occur in the olfactory cortex, which has formed its own nerve cell assemblies. The spatial amplitude pattern and carrier wave generated by the bulb and the cortex are different.

Thus, for odours that are familiar or may have biological significance, the formation of a NCA ensures that they are processed without delay in an adaptive manner. As to the question of how the brain recognises the presented odour regardless of which area of receptor cells are involved, the NCA would ensure that the message was distributed over the entire assembly before going to the bulb. If the bulb has been primed by arousal and the odour is known then an enormous burst of activity results. The bulb then sends a

"consensus statement" (Freeman, 1991b: 39) to the cortex which stands out and is distinguishable from the general level of activity because of its cooperative and synchronous nature. It is presumed that a similar event occurs when the olfactory cortex passes on information to the higher centres of the brain.

Although impossible to prove conclusively, Freeman maintains that Chaos exists within the olfactory system. He suggests that the basin of attraction for each attractor present would be the receptor neurons (NCA) activated during the reinforcement training. There exists many chaotic attractors, one for each odorant the animal can discriminate. The activity burst that takes place in the bulb and cortex can be seen as a bifurcation or phase transition from one state to another.

Skinner, Martin, Landisman, Mommer, Fulton, Milton, Burton & Saltzberg (cited in Basar & Bullock, 1989) have also studied the presence of chaotic attractors in the olfactory bulb of rabbits. Their results showed that the same odour can increase the dimensionality of the chaotic attractor (in crude terms can produce more Chaos) if it is novel rather than familiar. Thus, shifts in the dimension of an attractor are event related and are not related to the stimulus characteristics. They suggest that a general, global, chaotic attractor exists everywhere in the bulb and that the change from one attractor depends upon whether the odour is novel or familiar.

The application of such mathematical dynamics to neurobiological research has turned to concentrate on the change in dimensionality that occurs after an event, such as the presentation of an odour. Research by several authors has suggested that underlying molecular processes are themselves fractal and chaotic (Chay & Rinzel, 1985; Hess & Marcus, 1987). Why nature uses Chaos in this way has been suggested by Skinner et al (1989): it enables data compression before information storage. Gleick (1988) notes in his book that by giving two coordinates to the function that generates the Mandlebrot set it is possible to generate ten megabytes of exact pixel information. The problem for researchers is, given the pixel information, to identify the two coordinates and their chaotic dynamics.

A stimulus such as an odorant has certain physical characteristics but at the time of its encoding it is embedded in a context. When the situation demands the encoding of a novel stimulus and context, then more information has to be encoded. Skinner & Yingling (1977, cited in Skinner et al, 1989) have found that the thalamic gating mechanism allows more information to flow to the cortex when the stimulus is novel, and once the stimuli is learned or habituated then this mechanism suppresses the ascent of irrelevant sensory information. Chaotic dynamics require massive parallel processing capabilities to handle all the fractal data and Shepherd (1972) has demonstrated that this is the case with olfactory tissues which can then perform rapid on-line data compression.

In summary, it would appear that the olfactory system can be thought of as a massive parallel processor; a connectionist system that displays evidence of chaotic dynamics. There is no evidence yet to suggest that perception of olfactory stimuli, unlike in vision and audition is located at a specific location on the cortex. If the information at bulb and pyriform cortex level is in the form of a distributed ensemble code, then it seems plausible to suggest that perhaps this is the case when such olfactory information reaches the outer layers of the cortex, where it can be "read" using techniques such as EEG. This assumes that enough of the signal remains to be decoded.

EEG and Chaos

It would seem at present that there are two fields of EEG research, the classical and the "chaotic." The classical approach involves the use of techniques discussed earlier and treats data analysis mainly in a very traditional statistical manner. The chaotic approach is relatively recent and has developed largely as a consequence of mathematical advances in non-linear dynamics. The analysis of data produced by EEG is conceptualised and treated very differently by each approach and so far it appears that the new, chaotic view of brain functioning, coupled with advances in neural net theory, presents a more promising future for brain research. It is important to be aware however that the meeting ground for the two approaches is not yet clear and in fact it is too early to judge or

quantify the interface. This section will concentrate on the new view of how the brain may work.

Perhaps the greatest contribution of the new non-linear, dynamic view of the EEG is that it addresses the question of the functional significance of this phenomena directly. More traditional approaches have suffered because of a dearth of knowledge and effective modelling of the EEG. The brain has almost been considered as a black box. The new approaches allow researchers to peer inside the box and propose testable models of the hypothesized function of the EEG. In the following section a synthesis of all the pertinent factors relevant to this thesis will be presented with a discussion of the assumptions of both approaches to brain functioning and the consequences for the present study.

From the previous discussions it is clear that despite continuous EEG research for over half a century, field potentials detected on the scalp are still poorly understood in terms of their basic origin and functional significance. Bullock (1989) asserts that wide areas of ignorance still remain and underlines the need for further basic studies of this phenomenon. The wide use of the term synchrony is never explicitly quantified, nor precisely defined. There exists at present no way, despite neural modelling to:

"....specify the degree of coincidence expected by chance in the theoretical case of no synchrony, that is, all generators being independent, so that we cannot say when a small degree of synchrony is above the expectation of a null hypothesis. This is because known generators, let alone those unknown, are not simple dipoles and are not oriented in a readily knowable fashion, nor is the volume conductor isotropic." (Bullock, 1989: 543)

The mechanisms whereby synchrony may be established have also not been forthcoming. The use of the terms and concepts, "rhythm" and "oscillator" are also widely used without strong experimental foundation for suggesting that generators are oscillators (Bullock, 1989). The traditional view of the brain as a noisy processor (Adey 1972 cited by Mpitsos, 1989) that possesses statistical mechanisms which operate on this activity to

produce organised behaviour has almost outlived its usefulness. Difficulties in persisting with this view are many, not least because the lack of a conceptual model that accurately reflects the informational language that results from the interaction of small sets of neurons. Similarly, "circuit analysis" is not likely to lead to a full explanation of the emergent properties demonstrated by complex systems (Mpitsos, 1989). The nature and interpretation of "noise" has recently become a subject of intense interest because of the developments in the mathematics of chaotic, non-linear systems which allows for the first time an answer to the question posed by Adey (1972):

"Is it possible to envisage an information-processing system in which the very presence of an on-going noise-like activity produced no degradation in information-handling ability, and even enhance it ?" (Adey, 1972: 279)

The answer appears to be yes, thanks to the recent developments in dynamical theory and Mpitosis (1989) adds:

"We can go further and build on Adey's insight to say that while there may be many forms of noise even in brain function, among which we include variations having white spectra, or even invariant perturbations, variations arising from chaos cannot be separated from the information content of the signal because they themselves are an integral part of the information and are generated by mechanisms that need not contain explicit elements of noise." (Mpitsos, 1989: 522)

The importance of a conceptual model for the EEG is that it allows not only experimentation related to specific hypotheses, but it also makes possible a host of speculations that Chaos and all that it implies allows. For example it has been suggested that Chaos may have a role in the generation of behaviours related to survival such as rapid adaptation to changing environments. The practical sterility of the traditional approach is related to the fact that it is difficult to infer anything about a system by examining its output only. The only way to progress is from micro-electrode studies, to local circuit analysis to ERP, and EEG studies, a bottom-up approach that suffers because

of the lack of an overall conceptual framework. Researchers tend to concentrate on their level of analysis and often don't relate their model to other levels of analysis. As the work of Freeman (1987, 1989) ably demonstrates, solving sets of non-linear differential equations and invoking the concepts of Chaos and neural network theory means that it is possible to model the behaviour and output of neural masses, and their interactions that correspond closely to the observed signals. Thus it is possible to construct a model that accounts not only for single cell, local circuit and neural mass behaviour but which attempts to link global EEG activity with observed behaviours.

In essence, the chaotic approach to brain functioning suggests that the complex signal that is the EEG may be produced by a relatively simple non-linear system. As explained in an earlier section, Chaos that ensures the stretching and folding processes that occur in the phase space, allows a few elements of a simple dynamical system to generate complex behaviour. This is not to say that the EEG is produced by a simple non-linear system, it could arise from a complex non-linear system, but the possibility exists that a few key parameters underlie the range of dynamical behaviour exhibited by EEG. Some indications, such as the fact that although the EEG is a complex signal it is bounded by frequency and amplitude limits, and produces basic rhythms and waveforms, suggest that the chaotic model is a step in the right direction.

A characteristic feature of Chaos is the sensitive dependence on initial conditions which implies that similar causes do not produce similar effects, and this too can be postulated to occur in brain research. Basar (1985a) has demonstrated that there is a correlation between pre-stimulus EEG recordings and the evoked potential after stimulation. He suggests that the EEG is a quasi-deterministic signal that anticipates sensory-cognitive tasks. That is, if subjects have come to expect a rare tone in an auditory oddball task, and the rare tone is predictable, the EEG demonstrates reproducible patterns. The fact that the EP is affected by pre-stimulus EEG parameters suggests that the sought-for sensitive dependence on initial conditions (that demonstrates the presence of Chaos), exists in the brain (Jansen, 1991). If one accepts the possible existence of chaotic dynamics operating

within the brain, a discussion of how to interpret EEG findings in this light then arises and this is considered at the end of the thesis. In conclusion, a comment by Basar, on the impact of Chaos on the field of EEG:

"The important new trend demonstrating that the EEG is not pure noise but that it reflects chaotic behaviour stemming from deterministic signals should now cause much thinking on the part of those scientists who still link the EEG to the expression "epiphenomenon." It now seems probable that the EEG reflects one of the most basic properties of brain signalling." (Basar, 1988: 396)

CHAPTER FOUR

Discussion of data analysis issues in electrophysiology

For many studies the issues of experimental design and methods of data analysis may not be as crucial or as complex as they are for electrophysiological studies that are expensive, time consuming and produce prodigious amounts of complex data. The first criteria to be satisfied are that the exact purpose of the study should be clearly delineated and the second that there must be compelling evidence that the measures used, EEG in this case, must relate to the hypotheses. These points have been thoroughly dealt with in the preceding chapters. Gevins (1987b) has compiled a list of a complete analytic procedure which consists of:

"(1) experimental design, (2) data collection, (3) artifact rejection, (4) primary analysis, (5) data reduction (feature extraction), (6) decision (hypothesis testing), (7) validation, and (8) interpretation." (Gevins, 1987b 32)

It is important to remember that the analysis of topographical data will at times be different to the analysis of raw EEG signals. To a large extent the range of available and applicable methods are reduced with topographical data because the raw signal has been digitized, filtered and has been through a Fast Fourier Transform which has split the frequencies into the major bands. At each stage of the following discussion it will be made clear if the techniques mentioned are suitable for the present data set. Special problems for the analysis and interpretation of topographical data and their derived maps are highlighted. Further issues explored will be the difficulties of applying statistical techniques to such complex and highly variable data and the associated problems of interpretation. Several reviews of a limited nature are available on the interpretation of and the statistical issues surrounding topographic maps, the main theme being that great caution must be used if reliable and meaningful results are to be achieved (Oken & Chiappa, 1986; Kahn, Weiner, Brenner & Coppola, 1988).

Structure of the data and traditional methods of analysis

When statistical analyses are performed on data, certain assumptions are made about its structure. Statistics are useful because they allow the application of techniques that determine the extent to which chance contributes to the measurements under scrutiny. It is important to know how much chance contributes to electrophysiological measurements, in other words, to distinguish meaningful from noisy factors. This requires identifying the sources of variability in the data and attributing them to different factors. The importance of at least reducing the influence of random factors is why experimental situations are so carefully controlled across subjects and data samples. It may seem an obvious requirement but it must be kept in mind that the structure of the data under examination must generally conform to the requirements of the statistical procedure used (John, Harmony & Valdes-Sosa 1987).

In brain topography it is evident that multivariate statistical techniques are necessary, and furthermore, the added complication of spatial and temporal correlations involved in brain topography data mean that extra consideration must be given to the chosen method or methods of analysis.

As most tests assume a normal or Gaussian distribution, probably the most important task to execute before applying any statistical analysis is to examine the underlying distribution of the data. Multivariate normality is more difficult to achieve than univariate normality, because each variable individually and in combination must have a normal distribution. Thus, it is important to examine the distribution of the data before applying any statistical test that assumes a particular distribution. Statistical tests can be applied to data without a particular distribution in certain circumstances but great care must be taken in the interpretation of the results.

The problems in physiological testing paradigms and certainly in EEG recording, caused by the high degree of correlation between the variables deserve special mention. One of the major problems is ANOVA tests that violate the sphericity assumption (Vasey &

Thayer, 1987). This assumption is usually violated if two or more measures are taken from a subject closely spaced in time and if this occurs it means that the likelihood of a Type I error (false positive), exceeds the probability level set by the researcher:

"The assumption is violated if all vectors of difference scores, between pairs of correlations are not equally correlated. This is particularly likely to occur when "conditions" are separated in time or in space. For example, differences between adjacent conditions in a series are likely to be more highly correlated than differences among widely spaced conditions." (Collis, 1992: personal communication)

There are some solutions available to the researcher in this regard. A commonly used correction in the EEG literature to correct for sphericity is the Greenhouse and Geisser correction (Vasey & Thayer, 1987). This technique involves the reduction of the degrees of freedom but only protects the F test for the main effect of, or interactions with, repeated measures factors. Any sub-effect typically looked for after a significant main effect will be even more susceptible to a Type I error.

Analyses of variance with repeated measures have not been employed initially in the present study because of problems of suitability and interpretation. ANOVA is the systematic evaluation of the likelihood that two samples are drawn from the same population, in effect it evaluates the probability that the distributions of two samples are significantly different. This test looks at the effect of one variable across many groups, but if many variables are under consideration then a multivariate analysis of variance (MANOVA) is required. Electrophysiological data is characterised by a high level of intra- and inter- subject variability and the underlying assumptions of the ANOVA, namely a normal distribution, independence and equal variance among different groups are almost never met with this type of data. Added to this the ANOVA is a way of comparing means and it is commonly assumed that the average value or mean of some feature of a sample describes the typical value that would be found in a member of the population from which the sample came. However John et al (1987) note:

"However, one often encounters bimodal or multimodal distributions of a feature. By this we mean distribution curves with two or more peaks or maxima. Such distributions reflect the existence of subgroups within the population characterised by very different values for that feature. Thus the comparison of averaged EEG may obscure the existence of two different states within a subject, or a grand mean may obscure the existence of two or more subgroups in the sample selected for study." (John, Harmony & Valdes-Sosa, 1987: 498)

The problem of multidimensionality is often a concern in topographical mapping research and must be taken into account when interpreting the results of statistical tests and is allied in this study to the problems of sample size:

"A map consists of several readings, one for each electrode; usually one considers a sequence of maps, rather than a single one; each map may contain several features of interest; one may want to conduct several tests on the same set of data because of lack of subjects. The probability of obtaining a spurious result in such a situation can become enormous." (Wong, 1991: 156-157)

This problem is known as the p-inflation problem which means that there is an inflation of the Type II error, namely the probability of rejecting the null hypothesis when it should be accepted (Rappelsberger & Petsche, 1991). Abt (1983) suggests that significance testing of many variables, a particular feature of EEG studies including the present study, has not been thoroughly explored and too many studies ignore the implications of the p-inflation problem:

"Thinking in terms of multivariate parametric methods, the requirement of the data to originate from K-dimensional Gaussian distributions appears, even under generous aspects, to be entirely unrealistic. Even if this requirement could be fulfilled, multivariate analyses would not always be optimal since the experimenter usually asks at which particular location(s) differences between true effects presumably exist, a question which by means of multivariate models cannot be answered efficiently." (Abt, 1983: 48)

There are of course, some solutions to these problems. For instance, Bonferroni-adjusted probabilities can be computed which provides some protection for multiple tests. However, the great disadvantage with this route is the significant loss of power that results for the tests completed. Performing a preliminary multivariate test prior to using univariate ANOVA can also help reduce the p-inflation problem, but to do this there must be a good ratio of subjects to variables. This is not the case in the present study.

It is important for a study such as the present one to try and establish a balance between testing enough subjects, for a long enough period to characterise their EEG and any changes that occur in response to stimulation, and the practical and statistical problems involved in collecting prodigious amounts of highly intercorrelated and variable data. In this case statistics can hint at possible areas of interest and the p-values can be taken as descriptive (Rappelsberger & Petsche, 1991). It is also important to note that the present study is largely exploratory, partly confirmatory in nature. Therefore, regarding the p-values as descriptive and using them as a guide for hypothesis generation appears entirely justified.

The methods of analysis used in the present study initially are those that reduce the dimensionality of the data. With a study of this size the first priority must be to reduce the number of variables studied. An immediate ANOVA would not be the best analysis solution in the first instance. The data is highly variable and violates the assumptions of a normal distribution, equal variance and independance (sphericity) and stationarity. However, if the data was significantly reduced by a feature detection procedure such as a principal component analysis (PCA), then ANOVA may be employed on this feature set of data. In this case, the p-values could be used descriptively to guide further analysis and validation on other non-reduced data sets. Furthermore, previous studies of the effect of odour on the topographical EEG have employed data reduction techniques before the more traditional parametric analyses. Howells (1992) used multidimensional scaling techniques; Klemm & Warrenburg (1992) collapsed data from 20 electrodes to form four gross aggregates of the data; and Kendal-Reed used repeated measures ANOVA on only

a small subset of electrodes chosen on a priori grounds before the main analysis. Klemm et al (1992) gave no justification for their data reduction procedure other than to note that an ANOVA on uncollapsed data would be ill-advised because of the number of variables. Kendal-Reed (1990) relied on earlier work (Howells, 1992; Van Toller et al, 1992) to reduce the number of electrodes he studied, and these studies had in turn used MDS to reduce the dimensionality of the data. Thus it can be seen that in previous studies of the EEG response to odours the first task has been to reduce the number of variables studied. This is not to say that traditional methods of analysis cannot be used. After employing methods such as MDS or PCA, then the next best step is to employ ANOVA on the remaining variables.

Primary analysis in EEG

Frequency analysis

The design, collection and artifact rejection stages have already been covered in the thesis, so the first issue to be discussed here is the primary analysis stage. A popular and often used method in this respect is a frequency analysis of EEG. Period analysis, the type of analysis used by Lorig in his work with the EEG and odours, is the first kind. This isolates individual waves by measuring the zero crossings of the EEG, then the peak amplitude of each wave can be measured and the number and properties of the waves can then be tabulated according to the 'period' of the wave, i.e., the time between zero crossings.

A second form of frequency analysis however, and the one used in this study because of the design of the Brain Imager, applies a Fourier analysis to the raw EEG data. Here the EEG waveform is decomposed into its constituent parts. This means that the EEG data can then be represented by the sum of appropriately weighted waves of various frequencies, which results in the power spectrum. This process is more widely known as spectral analysis and the results are most often grouped into the traditional frequency

bands. The Fast Fourier Transform (FFT) algorithm is the most popular way of achieving this and is applied to short data segments, in this study 2.56 seconds of digitized data.

Spatial analysis

The role of primary spatial analysis in this study is also accomplished by the B.E.A.M software. The Brain Imager displays the maps of topographical activity which can be useful in the artifact rejection process, and can add some insights to the analysis procedure. In general the interpretation of such topographical maps is done by pattern recognition and Wong (1991) has identified three levels of analysis:

"Some of the primary spatial features that ought to be recognised first are peak, gradient and symmetry. Next there are secondary features like spread (the pattern of movement of a peak) and regions of persistent hypoactivity. Finally, one should formulate what the configuration of intercranial neural generators is that gave rise to this particular potential map. The objective of this last tertiary step is of course to be able to link particular anatomic structures to an observable electrical feature or activity." (Wong, 1991: 42)

Although Wong admits that this last step may be unsuccessful he suggests that even partial success would provide a useful insight. In this he is probably being too optimistic and fails to realise that the problems involved in interpreting EEG signal from the scalp that have been "smeared" (as detailed in Chapter 2) would caution against any attempt to locate generator sources from scalp recordings. The usefulness of his first two points are probably restricted to small scale studies with few subjects and would best be suited to clinical studies. For the present study with many subjects and many experimental conditions the dimensionality of the data increases dramatically which means that a direct portrayal of the distributions of the scalp patterns becomes impractical. To overcome such problems, techniques to reduce the dimensionality, (reduce the number of variables) must be sought.

Time series analysis

Many EEG analysis techniques assume that the EEG segment under investigation is stationary, i.e., that its mean and variance are time invariant. This assumption is rarely found in experimental situations where the EEG is being manipulated. A stationary time series signal is one that looks the same everywhere in time. To overcome the non-stationarity of the EEG signal the most often used approaches rely on autoregression techniques, whereby a present EEG sample is related to a weighted sum of the previous samples. The autoregression coefficients can then be used to estimate the power spectrum of the EEG signals under study. As many as 10 electrodes can be modelled effectively in this way (Gersch, 1987) but it is particularly computer intensive.

The assumptions of such a process are:

"In the case of the analysis of an EEG signal by parametric methods based on such models, it is assumed that a linear filter describes the process of EEG generation; this filter is fed with a signal having a constant spectral density, i.e., white noise; the output, i.e., the EEG signal, has a spectral density which is dependent upon the properties of the linear filter. The statistical characteristics of this output signal can then be determined by relating the value of a time sample to the value of the past samples, that is by using regression of the signal onto itself. This is why this method is called autoregressive." (Lopes da Silva & Mars, 1987)

Segmentation of a longer EEG record can also use autoregressive techniques. A segment of EEG is modeled using autoregression and the resulting model is then used to predict the next segment. As soon as the model fails a new model is created on the new EEG segment. The resulting segments can then be analysed using statistical pattern recognition techniques. The determination of the point in time where the model fails and a new segment is started is a critical issue in this analysis. Gersch (1987) has provided some useful thoughts on the topic of non-stationary multichannel, multivariate time series analysis and concludes that:

"The literature on multivariate time series modeling is surprisingly sparse considering that many natural and social science phenomena are non-stationary...The inherent problem in modeling multivariate time series is the tendency to overparameterize those models." (Gersch, 1987: 283)

Time series analysis is not suitable for the present study because the time series under analysis is too short. This method is considered further, in the last chapter of the thesis.

Feature extraction and standardisation in brain mapping

After the primary analysis, there is the feature extraction stage, a complex but necessary step in the entire analysis process. A feature is a summary of some important aspect of the EEG record. John, et al (1987) identify five different classes of problems that may occur in the evaluation of quantitative features extracted from complex clinical data sets:

"(a) can the population be classified into different categories ? (b) Are different patterns of values characteristic of patients with different clinical symptoms ? Can the clinical systems be meaningfully related to the associated electrophysiological features ? (c) Do different feature patterns characterise differences in outcomes ? (d) Is there any evidence that some groups of patients, apparently homogeneous by clinical criteria, might contain heterogeneous subgroups with different physiological profiles ?" (John et al, 1987: 499)

This list can obviously be modified to suit individual study requirements. For instance, in this study we can ask: (a) Can the group of subjects be classified into different groups on the basis of which odours were presented ? (b) Can the presentation of a particular odour be related to the pattern of the EEG ? (c) Do these feature patterns differ for different odours ? and (d) Is there any evidence that some feature patterns related to the presentation of odours differ for males and females, for time of day etc ? The use of statistics in answering such questions is mostly obligatory.

The main aim of the feature extraction process is to meaningfully reduce the amount of data generated from the primary stage of the analysis. The most well known method and

one used in the present study is principal components analysis (PCA). In PCA, the differences between conditions are initially ignored, and are treated just as any other source of variance. This procedure then seeks a smaller number of mutually uncorrelated linear combinations of the original variables. The components can then be treated as "ordinary" variables in a between-condition analysis. The main drawback of the technique is that the small amount of residual variance left unaccounted for by the main components may well be crucial for distinguishing between different experimental populations. Also, the fact that the best combination of the variables is linear may not lead to the extraction of the most useful combination of the variables (Gevins, 1987c).

An alternative method of feature extraction is the application of statistical pattern recognition algorithms of which the most popular is discriminant analysis or stepwise discriminant analysis (SDA). In contrast to PCA, the focus from the start is the between-condition variance. This method chooses the variable for which the ratio of between-condition variance to within-condition variance is greatest, then selects the next variable removing most of the variance unaccounted for by the first chosen variable, and so on until all the variance is accounted for. The major drawback of this technique is that the set of variables chosen this way, one at a time, is less effective than choosing the variables in combination, even with stepwise addition and deletion. It has been suggested that to overcome this problem known as Cover's paradox (Gevins, 1987c) then all possible combinations of the variables must be computed but obviously in a study of this size this is not a practical option.

It is possible, as outlined above, to capture the best of both SDA and PCA, by performing a MANOVA first. If a MANOVA is used as a test of differences between conditions, then the dimensionality of the data can be examined by performing what is essentially a PCA on the between-conditions covariance matrix. However, the problem of the ratio of subjects to variables still remains. An accepted guide is that a minimum of 10:1 is necessary, with a preferred target of 20:1 (Collis, 1992: personal communication). This is not the case in the present study. The most useful way of analysing the present dataset

was to apply feature detection analyses first i.e., PCA. When the dimensionality of the data has been reduced by this technique, then more parametric methods such as ANOVA can be applied. The immediate aim of the analysis is to reduce the number of variables under consideration, to reduce the dimensionality of the data.

Standardising features has always seemed an attractive procedure when it is considered that records from a number of subjects will vary considerably because of a number of factors, such as skull thickness and conductivity, physiological state, and metabolic influences. Such techniques as zero mean and unit variance have been used to accomplish the task of converting each person's record into standard scores. This is not so simple however, there are many methods of standardising scores and the pro's and con's of each procedure have not been fully explored, so there is no agreed best method. It is clear that more research is needed in this area.

Coherence analysis

A popular method of dealing with EEG data is to use the coherence function, which quantifies the association between pairs of signals as a function of frequency (Shaw, 1981, 1984; Shaw, O'Connor & Ongley, 1978; Swenson & Tucker, 1983; French & Beaumont, 1984; Rappelsberger & Petsche, 1988;). This technique intrinsically addresses variation in the time domain and the covariation between spatially distinct sites.

"It measures the correlation within discrete frequency bands for selected epoch lengths and is mathematically independent of signal amplitude." (French & Beaumont, 1984: 241)

The use of coherence analysis has been mainly to study task-induced changes in the EEG related to the functional organisation of the brain, and the ways in which patterns of EEG amplitude fluctuation differ between hemispheres and different pathological groups. The majority of coherence studies use a limited number of channels, and while this type of analysis was considered for the present study, it also became obvious that its success

would be enhanced if the number of channels could be reduced by feature detection analyses first. One of the major obstacles to implementing coherence in the present study was the amount of data to be studied:

"Whereas the problems with data handling and interpretation of power data increase linearly with the number of channels, these problems increase geometrically with the number of channels in coherence analysis. With N channels (N^2-N) /2 unique comparisons can be made." (Swenson & Tucker, 1983: 61)

Several methodological problems, reviewed by French & Beaumont (1984) also mean that a comparison of the results generated by different research groups is difficult. For the present study, coherence analysis was considered to be inappropriate given that the first aim of the analysis was to try and reduce the number of variables involved. Furthermore, the use of such an analysis to characterise the change in EEG related to the presentation of an odour which may result in extremely fast physiological changes is questionable:

"Coherence has been much used in studying various psychiatric populations, and it is possible that a common pattern of inter- and intrahemispheric coherence characterizes certain learning disorders. Simple differentiation of clinical groups is a valid, if limited, use for coherence, but any attempt to go beyond this and interpret the meaning of any differences is fraught with problems." (French & Beaumont, 1984: 250)

Decision and hypothesis testing

This constitutes the most important part of the analysis and goes directly to the question of whether the hypothesis is supported by the data. This can be achieved by parametric or non-parametric techniques, univariate or multivariate tests. If the results from the feature extraction process are clear then statistical tests can be applied to support the conclusion that is suggested. More often that not, however, with electrophysiological data the results of such an analysis are not clear and statistical tests must be used to explore the data further.

Validation

If extensive and exploratory data analysis has been undertaken then it is vital that a process of validation is carried out to determine if the results are significant, reliable, and capable of being replicated and are physiologically meaningful (Gevins 1987b). The optimum way to carry out such a validation is to gather an entirely new and independent data set. But this may be impossible for practical reasons, in which case a portion of the data collected can be left out of the original data set analysed and used for validation procedures. This can be repeated many times each time leaving out different portions of the data. Maus & Endressen (1979) in a discussion of the misuse of computer generated results suggest that the data collected should be split into two halves resulting in a generating hypotheses half and a testing half. Obviously the criteria on which this decision is based should be made explicit. In this study, the data from the third testing session (second main experimental study) has been reserved for validation, the first two testing session data being the hypothesis generation sample.

Difficulties, hypotheses & predictions

An important point to note is that if specific hypotheses are able to be formulated then the experimental design and data analysis are, if not straightforward, relatively easier than if the hypotheses are not clear in advance of the inception of the study. This is the difference between a confirmatory and an exploratory analysis. This study is in part confirmatory and in part exploratory both of which will be clearly identified in what follows. A caveat to be kept in mind is that conducting exploratory research in this area has to be thoroughly detailed because of the intrinsic difficulties of EEG data collection and interpretation:

"The problems of random selection and multiple comparisons become very relevant in an observational study and the p-values become more "qualitative" indicators. This difficulty is particularly acute in brain topography, where the variety of problems to be studied and the lack, in many areas, of solidly established criteria for clinical assessment,

lead researchers to use large amounts of data collected on few subjects to provide answers to many questions." (Wong, 1991: 181-182)

As such the results of the exploratory phase of the analysis should be viewed as hypothesis generation and an attempt to bring a systematic approach to the study of the effect(s) of odours on the EEG.

The task at this point is to determine what questions we can expect to be answered using B.E.A.M to study the brain's response to odours. From the considerations in the first chapter it is clear that coding in the olfactory system up to bulbar level is temporal with spatial modulation. It would seem from the work of Freeman that it is possible to detect behaviourally relevant odour information in the EEG, at bulbar level (in rabbits). It is not known at this time what sort of coding of odour information occurs at the higher olfactory areas in humans, but it seems reasonable to assume at this stage that the process results in a diffuse spatio-temporal signal at the higher levels of the cortex. This view gains support from the fact that, as yet, olfaction has no identified location on the neocortex. We may expect then that the EEG would contain odour related information. The studies of Lorig show that the perception of an odour can modify the EEG but that careful attention must be paid to the source of this change, either the physiological effect of the odour or the cognitive processes that occur when an odour is perceived. Van Toller and colleagues (1992) have progressed to the point of suggesting groups of electrodes that respond differentially to different odours and respond to psychometric dimensions. The available studies continue to suggest that any EEG changes in response to an odorant are likely to be in the alpha or theta wavebands, but as the effect of attention and arousal occur here, any results must separate out the possible confounding factors.

We may expect some hemispheric differences. At least three pieces of evidence combine to give this view; some research has suggested a superiority of the right hemisphere at least for odour recognition (Hines, 1977; Richardson & Zucco, 1989; Zatorre & Jones-Gotman, 1991); the right hemisphere seems better suited to the processing of unitary phenomena (Tucker, 1990), and odour memory researchers have suggested this is how

odours are perceived (Engen et al, 1991). The right hemisphere has been implicated in phasic arousal and the orienting response (Tucker, 1990) and so we may expect novel odours to elicit more of a response in the right hemisphere and finally; the right hemisphere has long been regarded as more involved with the processing of emotional experiences and odours are linked with emotions (Van Toller, 1988).

However, despite the above, it remains to be determined how these hemispheric effects may be reflected in the EEG. Should there be more or less power in each waveband, or will the frequency be affected differently for each hemisphere ? At this stage all that can be said is that there may be hemispheric differences. If these do occur with the exception of the orienting response which should occur only with novel odorants, then any of the above may explain the result, It can also be noted that presentation of a novel odorant may produce "alpha de-synchronisation or blocking" the phenomena associated with arousal. Another factor that may militate against the detection of hemispheric effects is the B.E.A.M equipment itself. Because the Imager performs an FFT transformation on the data it is not possible to assess the proportion of power in each waveband relative to the amount of total power.

Hypotheses can be formulated as follows:

(1). Brain electrical activity mapping will show differences in a no-odour condition as compared to an odour condition across/within subjects.

(2). The topographical patterning of the B.E.A.M. response will differ reliably depending on the odour type across/within subjects.

(3). The topographical distribution of the B.E.A.M. response may differ depending on the psychometric response given, across/within subjects.

Thus, this study will examine the topographical EEG response resulting from an odour presentation. However, it is important to note at this stage that a study of between subject effects may have to be compared to within subject effects. Averaging the data or using

summary statistics may be useful up to a point but in the following results section it is also made clear that such analyses may have limited validity because of the variability of the EEG:

"Group data may be misleading, particularly for topographic maps. The point is that there is no single 'normal' map that represents the scalp distribution for the alpha rhythm, but rather several different clusters of alpha types. This is a possible problem for any kind of multivariate analysis, and it complicates determination of the normal range of variability." (Coppola, 1990: 41)

It must be noted that the anticipated "most useful" wavebands will be alpha and theta, because of the results from previous studies, but all the wavebands will be examined. Also, the temptation exists in studies such as this which have a large database and an exploratory component to try many different analyses in order to find "something" of significance paying little attention to underlying justifications and the problems of interpretation:

"Fishing expeditions are dangerous enough in the area of univariate statistics - in multivariate statistics, they are reckless." (Wilkinson 1989: 97)

In the present thesis it is hoped a reasonable compromise has been reached between acknowledging the difficulties of analysing such complex data and applying data analysis procedures that do not unreasonably violate underlying assumptions.

CHAPTER FIVE

Methodology

Olfactory evaluation study - Introduction

A group of thirty-nine undergraduates agreed to participate in the olfactory evaluation test. The purpose of this test, was to test the olfactory ability of the subject group. Any results generated at this stage could be correlated with the EEG data, or may assist in the interpretation of the results generated in the main experimental studies. A further reason for this evaluation was to introduce students to the olfaction laboratory and to the olfaction testing situation. The results of the evaluation procedure were not anticipated to have a major impact on the main study. The test was provided by Quest International.

Method

Subjects

Thirty-nine undergraduates aged between 18 and 45 participated in the evaluation tests. Of these 26 were female and 13 were male. All subjects were screened for current illness and respiratory tract infections, and the female subjects were asked to give menstruation details.

Evaluation tests

There were four main evaluation tests for the subjects to complete: an odour memory test, which was administered in four parts; an odour intensity test; an odour discrimination task; and an odour identification task.

Stimuli

Odour Memory Test

The odours for the memory test were placed into groups of three as follows:

Table 1.5.1 Odours for the memory test in the olfactory evaluation study

Group One	Group Two	Group Three
Femme Rochas	**Tuberose**	**Fresh**
Chanel	muget	tarragon
Red Ruby	jasmin	green vegetable

Each of the odours was placed on an absorbent wick, each contained in a small plastic cylinder, known as a soborod. This is a small, circular plastic container (1.5 inches in height, 1 inch in diameter) containing a wick that can be saturated with an odorant. The odours in bold typeface are the "target odours" presented together to the subject at the beginning of the experiment. The two remaining odours in each group, formed distractors when the subjects were asked to recall the target odour.

Odour Intensity Test

For this test, four different concentrations of hyacinth dissolved in dipropylene glycol, were placed in a small glass jars. The concentration levels were, 10%, 2%, 1%, 0.1%. A fifth jar contained only dipropylene glycol and formed the blank.

Odour Discrimination Test

Note: DEP, is diethyl phthalate an odourless solvent. The animal odour was civet.

This test involved six odour triangle tests. An odour triangle test consists of a group of three odorants, two of which are the same, the third being perceptually similar but different. The groups were as follows; Triangle one, spearmint, peppermint,

spearmint; Triangle two, spearmint, peppermint, peppermint; Triangle three, DEP, DEP, Galaxolide; Triangle four, Galaxolide, DEP, Galaxolide; Triangle five, DEP, animal, DEP; and Triangle six, DEP, animal, animal.

Odour Identification Test

Ten odorants; green, apple, rose, lavender, cinnamon, cedar, vanilla, Johnson's Baby Powder, sage, and a hospital smell, were placed in small, numbered, glass jars.

The subjects were given an instruction and answer sheet on which to complete their answers to the odour intensity and odour discrimination tests. The experimenter completed a second answer sheet with the subjects' answers to the odour memory and odour identification tests. Examples of these forms are in Appendix 2.3.1 & 2.3.2

Procedure

Subjects were given a instruction and answer sheet when they entered the laboratory, and the main aim of the evaluation tests was explained. The order of the tests was fixed for each subject as follows: presentation of the target odours, odour intensity test, first odour memory test, odour discrimination test, second odour memory test, odour identification test and the final odour memory test. It was stressed by the experimenter at all times that any labels that appeared on the containers were coded and were relevant only to the experimenter and should be ignored.

Tasks

Odour Memory Test

The subjects were presented with the three target odours, informed that they could smell the odours repeatedly if they wished, and asked to remember them. Subjects were then told that later on, each of the odours would be presented with two distractor odours, i.e., memory group one, two or three, as given above. Their task on each occasion was to identify the target odours they were currently smelling. The three memory test groups, were presented in a random order between the other evaluation tests.

Odour Intensity Test

Subjects were presented with the five glass jars and asked to read the appropriate instructions on their instruction and answer sheet, while the same instructions were given verbally for emphasis. The subjects were required to smell the contents of each of the five jars and to place them in order of intensity from the strongest to the weakest. They then transferred their answers to their answer sheet.

Odour Discrimination Test

Subjects were presented with the odour triangles, in exactly the same order as outlined above. The order was invariant across subjects. The subjects were asked to read the relevant instructions on their sheet and received the same instructions verbally. Their task was to smell the contents of one odour triangle at a time and to pick out the perceptually different odour. They then transferred their answers to the relevant part of their answer sheet.

Odour Identification Test

Subjects were presented with the ten glass jars and asked to smell the contents, as given above, and name them. The order of presentation was invariant across subjects.

Results

Below is a table of descriptive statistics for the evaluation data:

Table 1.5.2 Descriptive statistics of evaluation study data.

	Intensity	Triangle	I.D	Memory
No.of Cases	39	39	39	39
Mean	3	5	4	2
Minimum	0	1	0	1
Maximum	5	6	9	3

As can be seen from the table, only one category, that of identification, failed to achieve a maximum score probably because to name an odour is a more difficult task than detecting perceptual differences. It has often been noted that the olfactory ability of females is superior to that of males (Cain, 1982). However, the table below shows that this was not the case in this evaluation study, perhaps a reflection of the relative lack of sophistication of the test rather than of the genuine ability of the subjects.

Table 1.5.3 Evaluation study descriptive statistics by gender

	Female	Male	Test
No. of Cases	26	13	--
Mean value	3	3	Intensity
Mean value	4	5	Triangle
Mean value	4	4	I.D.
Mean value	2	2	Memory

The reason for the lack of difference between males and females could be because the test itself is short and lacks sensitivity, or it may be that the sample sizes are too unequal to permit any reliable interpretation of the data. The results of this test have been placed before the main experimental work because they are not expected to play a major part in

data analysis or interpretation. The main conclusion to be reached from this analysis is that all subjects show a reasonable olfactory ability, with some better than others. The test was not sophisticated enough to identify subgroups in the general subject population.

Main experimental study I - Introduction

The main aim of the experimental testing situation was to provide a comfortable and relaxed atmosphere for the subject in which the presentation of the odour would be confounded by as few variables as possible. Conditions were created such that each subject was tested in a replicable, controlled environment. All subjects were tested in a specially built low-odour room (LOR). The details below are taken from Kendal-Reed (1990: section 4.8.4) who used the same room for his study of infant EEG responses to food odours:

"Mean temperature inside the LOR was 20 degrees Celsius. The LOR was fitted with a virtually silent, high-capacity ventilation system which provided 18 complete air changes /hour. Dimensions of the LOR were; 2.2 metres high; 1.8 metres wide and 1.6 metres deep. The internal volume was therefore 6.7 cubic metres. [The LOR also had] anodised aluminium wall and ceiling linings, continuous use of a ventilation system; regular filter changes, special ceramic tile construction of floor, sealed with polyurethane sealing compound to minimise odour from the tile grouting, strictly no use of non-experimental odorous material within the chamber and regular 48 hour application to the floor of granulated magnesium silicate (Steetley Minerals Ltd) to absorb any residual odours." (Kendal-Reed, 1990: 110)

The advantages of testing in such a chamber are twofold. It allows the ambient odour level to be reduced as far as possible to reduce confounding odours and to maximize the impact of the stimuli. Also it shields the B.E.A.M equipment from electrical interference. Subjects were seated in a comfortable chair so that they could relax and the EEG recordings would be less at risk from muscle contamination. This however, increased the risk that the subject would become too relaxed and so between each period of data

recording the subjects were asked how they were and their thoughts on the experiment so far, and allowed to move about a little. This is recommended by other researchers:

"The records were separated from one another by a period of rest while the subject was allowed to move head and limbs. During this resting interval, the subject was interrogated about the impressions of the just performed task or control period. This not only yields additional personal data on performance strategies for each task but also the purpose of maintaining the person in an approximately constant state of alertness." (Rappelsberger & Petsche, 1988: 47)

The stimuli were also controlled as much as possible. They were diluted until they were judged to be iso-intense by 10 adult researchers. This is important as it ensures reasonable control for intensity which may affect the EEG. It is also known that smoking and menstruation can be detrimental to olfactory acuity but these factors have not been controlled for in this study as it is not clear to what extent they would affect the EEG. All of the stimuli are supra-threshold which means that olfactory acuity is not an important variable. It has been noted however which subjects are smokers and which female subjects were menstruating at the time of testing.

Consideration of the effects of gender, hemispheric differences and handedness of subjects is more problematic. It is well established that male and female brains are different, each cerebral hemisphere exhibits gross differences in function and that handedness is related to hemispheric dominance. This study is not designed to be a study of such factors. The first requirement in this study was to demonstrate a change in the EEG to an odour, using B.E.A.M. Once such a change has been demonstrated and any topographical effects related to the type of odour presented, then a search for the effects of the above variables can be undertaken. The position taken in this thesis is that the confounding effects of these variables is low, so that note has been taken of the gender and handedness of the subjects' but the data has not been analysed separately by gender or handedness. Hemispheric effects it is hoped will emerge through the data analysis

procedures. For example showing a possible right hemisphere dominance in the processing of novel odours.

The subjects used in this study were tested in the morning and the afternoon of the same day. The aim of such a design was to explore the stability of the response to odours and any diurnal variation. This thesis has a longitudinal element and an examination of the time frame over which the response to odours is the same or different was thought necessary, hence the testing in the morning and the afternoon of the same day and testing again one year later. It was hoped that in this case any results generated in the first part of this study could be validated and extended on data collected in the second main experimental study.

Method

Subjects

Thirty-eight undergraduates aged between 18 and 45 years participated in the experiment. Of these 28 were female and 12 were male. All the subjects were screened for current illness and respiratory tract infections, and the female subjects were asked to provide menstruation details: 9 were menstruating at the time of testing. Of the group 17 subjects were smokers, 21 were non-smoking and 6 of the group were left handed, compared to 32 who were right handed.

Equipment

A Neuroscience Series III Brain Imager was used in this study. For a full presentation and discussion of the technology the reader is referred to Appendix 4.

Stimuli

Twelve odorants were used. Group one included eight fine fragrances: Pink Quartz, Red Ruby, Imperial Jade, Green Emerald, Purple Amethyst, Yellow Topaz, Golden Amber, and Blue Diamond. All of the fragrances were dissolved in dipropylene glycol and were

at 20% concentration. The remaining odorants in group two were: iso-valeric acid, this was at 0.22% concentration in dipropylene glycol; androstenone, at 0.1% concentration in ethanol; linalyl acetate was at 100% concentration, and finally traseolide was at 20% concentration in dipropylene glycol. With the exception of androstenone all these odorants were prepared and supplied by Quest International. To some extent the odours other than the fragrances were chosen arbitrarily to include odours that are psychologically and perceptually interesting, and to include at least one unpleasant odour. Two blank perfumers strips formed the controls, one for group one, and one for group two.

Preparation of the odours

In all cases 50µl of solution was pipetted on to one end of absorbent perfumers smelling strips. The strips were dried in a fume cupboard and then each was suspended in a test tube after their top was wedged into the bottom of a cork that acted as a stopper in the test tube, see Appendix 2.2.1. Fresh odorant strips were prepared weekly, but linalyl acetate and traseolide were freshly prepared twice weekly to prevent a loss of intensity. All odours were kept refrigerated until an hour before use to preserve their freshness. The middle note of the odours was almost certainly being presented to the subjects. See Appendix 2 for details of the structure of perfumes and their evolution after application. The two blank strips were changed after every testing session.

Procedure

All subjects were given a handout at least a week prior to their testing date. This asked them to refrain from eating any strongly spiced food the night before testing, and on the day of testing to avoid the use of any strongly smelling product especially perfume, after-shave, soaps or bathstuffs. They were also asked not to use hair-spray or hair-gel which might interfere with the electrodes in the headcap.

During testing the experimenter wore a laboratory coat and disposable plastic gloves throughout each of the testing sessions. The gloves had a distinctive odour but it was

considered that this would be controlled for by their use across all subjects. In addition, the gloves were aired for an hour in the fume cupboard to reduce their odour. The subjects were tested in the morning and the afternoon of the same day, with a six hour gap in between.

Testing Session One

The subjects were welcomed into the laboratory and seated in a comfortable chair and the headcap was fitted. During this procedure which took approximately half an hour, the subjects were asked to complete a subject information form, a copy of which is in Appendix 2.3.3. They were then taken to the low odour room, and seated in a reclining chair. The subjects were told that they would be wearing headphones, through which white noise would be played, and goggles. The white noise was set at a comfortable level by the subject, typically 90 dB. These procedures were used to provide a perceptually impoverished environment and reduce the amount of perceptual cuing. See Appendix 2.4.3 (photograph of a subject in situ).

In order to prevent retronasal stimulation of the olfactory receptors during testing the subjects were required to breathe in through their nose and out through their mouth. They practised this technique while the experimenter prepared the Imager for recording. Subjects were told that there would be 14 recording periods, each of approximately half to one minute long, and that they would be informed of the start and finish. During a recording period they were to breathe as they had been taught and to remain as still as possible. They were told that they may or may not detect an odour during the recording periods, but that if they did they must try not to move or speak but were to concentrate as much as possible on the odour without trying to name it. Between the recording periods they could move and breathe as they wished to remain comfortable.

The odours were presented to subjects on a perfumers' smelling strip, held approximately 3cm below their nose. Group one, the fine fragrances, were always presented first in order to preserve subject's fine discrimination, but within a group the odours were

presented in a random order. Prior to each recording session the subjects were reminded to breathe as they had been taught and to relax. The inter stimulus interval, when the subject was allowed to move, was at least one minute and usually about three.

The subjects' EEG was recorded for fifteen frames, the odour presentation occupying four of these. The procedure was as follows: frames 0-4 no odour, frames 5-8 odour presentation, frames 9-15 no odour. Presentation of the odour was synchronised with the onset of frame five. This was the same for all subjects.

Testing Session Two

Each subject was tested for the second time, six hours after their first test. The above procedure was repeated exactly. After completing this test however, each subject was brought back into the laboratory and asked to re-smell the odours and to rate them on analog bipolar scales for; familiarity/unfamiliarity, pleasantness/unpleasantness and strength/weakness. The scales were counterbalanced to prevent any order effects, and an example of the rating sheet is given in Appendix 2.3.4.

Main experimental study II - Introduction

The procedure followed in this study was almost the same as in the above study. The differences were that breathing patterns of the subjects' were monitored more closely, more frames of data were recorded per trial and some of the stimuli were different. After the first study, an improvement in design for this study was to synchronise the presentation of the odour with the inhalation cycle of the subject. If, as was suspected, the effect of an odour on a subject's EEG is neither dramatic in the majority of cases, nor easily demonstrated, then precise knowledge of the moment of inhalation would be a distinct advantage. For this purpose a transducer was positioned around the chest of the subject and the data from this was recorded on a spare signal channel on the Imager.

A further change was the odours used. Five odours were the same and two additional odours were dilutions of one of these five; five odours were fine fragrance creations developed by Quest International; two blank strips formed controls as before.

More frames of data were recorded in the belief that it may help to provide a more reliable "baseline". To this effect instead of five pre-odour frames, there were twelve pre-odour frames. The number of odour presentation frames remained the same at four frames, and the number of post-odour frames was similarly increased from four to ten.

Method

Subjects

Sixteen undergraduates from the original subject group, aged between 18 and 44 participated in the third testing session, one year later. Of these, 11 subjects provided usable data. Of these subjects, 6 were female and 5 were males. None of the women were menstruating at the time of the test, the subjects were all non-smokers and they were all right handed.

Stimuli

The five original odours used here were as follows: Golden Amber, Red Ruby, Blue Diamond, Pink Quartz and Yellow Topaz. All of these odours were dissolved in dipropylene glycol at 20% concentration. The two dilutions were of Blue Diamond in dipropylene glycol at 1% and 0.25%. The new odorants were created by Quest International specifically for the present study. These odours were at 20% concentration in dipropylene glycol. When these odours were presented on perfumers' strips they were presented "wet", that is, a small amount of the odour (200 micro-litres) was pipetted into the test tube and the experimenter ensured that the smelling strip was dipped into the odour immediately before presentation. This was to ensure the "top note" was received by the subject. See Appendix 2, for details of perfume structure and their evolution after application.

Procedure

The subjects were tested only once during the day, their EEG activity was recorded for 25 frames, and their breathing rate was monitored. The progression of frames was as follows: frames 0-11 no odour, frames 12-15 odour presentation, frames 16-25 no odour.

CHAPTER SIX

Results I

Psychometric report - Introduction and statement of aims.

Psychometric data has been collected in these experiments for two reasons. First, it may be correlated with the psychophysical data collected on the Neuroscience Series III Brain Imager. This may tell us, for instance, if the perceived attributes of an odour are related to topographical EEG recordings. Secondly, because data has been collected in this research programme for hypothesis generation purposes, the analysis of psychometric data may provide clues as to how the main data set should be analysed. For example, if large differences were found between the psychometric ratings of males and females then this would suggest that their psychophysical data be analysed separately. The assumption being that any strong "group" differences in psychometric rating behaviour may be reflected in differences in topographical EEG data.

As an aid to explain some of the terms used in this report, a brief discussion of perfumes and their nomenclature is given in Appendix 2. It is suggested that this section is read first, before proceeding further with the present text to serve as an introduction to some of the terms used later on in the report.

After the first main study testing session in the afternoon, subjects were brought out of the low odour room into the laboratory, presented with the test tube rack containing all the odour strips. They were then asked to rate all the odours on three psychometric scales starting with the first odour and proceeding to the last odour in the order they were given. They were allowed to smell the strip as often as they wished, although the majority did not go beyond one sniff. The odour rating scale was a simple line scale with a mid-point at 5 cms. The odours were rated along three dimensions: weak / strong, unpleasant / pleasant, and unfamiliar / familiar. An example is given below. The scales were randomised and rotated to counteract any order effects.

Weak _____/_____Strong

Subjects were required to break the line at a point where they judged the stimuli to be on that particular dimension. They were also instructed not to concentrate on a narrow band of the scale but were to use the full range. The scales were scored by simply measuring the distance from the weak, unpleasant and unfamiliar dimension to the subjects' mark. In other words the lower the score (under 5) the more weak, unpleasant or unfamiliar the odour, the higher the score, (over 5) the more strong, pleasant and familiar the odour. (this holds true for all of the tables in this report).

The data presented below has been thoroughly analysed to find the most psychometrically diverse odours for use in the analysis of the EEG power data. A subsidiary theme running through the following is the intrinsic interest of the psychometric ratings. A general finding in olfaction literature is that females generally outperform males on tests of detection, discrimination and identification (Cain, 1982; Doty, 1991). There is some evidence that this superior ability is present at birth and may be linked to a genetic trait (Makin & Porter, 1989). An additional finding in the olfaction literature is the reduced olfactory ability of smokers compared to that of non-smokers (Doty, 1991; Dunn, Cometto-Muniz & Cain, 1982; Frye, Schwartz & Doty, 1990). This effect however, is not as marked as the gender differences. Interestingly, the reduced acuity in smokers relates also to past smokers whose olfactory ability does not return quickly, this recovery being a function of their past dosage. A smaller effect that may also be detected is that the olfactory acuity is reduced in females who are menstruating (Engen, 1982). Threshold measurements show that female olfactory acuity is best at the time of ovulation and poorest at menstruation. This is thought to be because of mucus levels associated with varying levels of hormones. How far these findings relate to the present study will be considered but it must be remembered that these are not the primary aim of this thesis.

Analysis of the psychometric data collected in the first main experimental study.

Table 1.6.1, below, shows the mean subject rating (in descending order of magnitude) on each of the dimensions for all odorants except androstenone which will be discussed later on in this thesis.

Table 1.6.1 Mean subject rating for each psychometric dimension (n=38)

Notes: The first number in brackets indicates the mean rating for that odour for that dimension. The second figure indicates the rank order of that odorant on that dimension. Standard deviations are given in italics. Two blanks were presented and were correctly identified as such by 95% of the subject group.

Odour	Strength		Pleasantness		Familiarity	
IVA	(8.2) (1)	*2.3*	(0.9) (11)	*1.2*	(6.8) (2)	*2.9*
G. A	(7.7) (2)	*1.4*	(6.7) (5)	*2.1*	(6.7) (3)	*2.7*
Y. T	(5.6) (10)	*2.6*	(7.1) (2)	*1.8*	(6.7) (4)	*2.2*
B. D	(7.3) (3)	*2.3*	(6.7) (4)	*2.1*	(6.8) (1)	*2.4*
G. E	(7.3) (4)	*1.8*	(6.7) (3)	*2.4*	(6.3) (7)	*2.3*
R. R	(7.3) (5)	*1.9*	(5.6) (9)	*2.6*	(5.4) (10)	*2.8*
L. A	(7.2) (6)	*3.1*	(6.1) (7)	*2.8*	(6.6) (6)	*2.9*
I. J	(7.1) (7)	*2.1*	(5.5) (10)	*2.6*	(5.9) (8)	*2.6*
P. A	(7.0) (8)	*1.7*	(5.9) (8)	*2.6*	(5.7) (9)	*2.5*
P. Q	(6.1) (9)	*2.3*	(7.3) (1)	*2.1*	(6.6) (5)	*2.6*
Trase.	(3.6) (11)	*2.9*	(6.4) (6)	*2.7*	(5.1) (11)	*3.2*

It can be seen from Table 1.6.1 that as a group the subjects found only one odour weak, and only one odour unpleasant. This is perhaps not surprising considering the nature of

the odorants used, the sample set being composed mainly of fine fragrances. The graphs given in Appendix 5 (psychometric graphs) give individual score distributions for each odour. The graphs show the wide variation in individual perceptions of strength that may be a consequence of the differences in individual thresholds for each odorant. However, overall there are no large differences in strength ratings for any of the odorants except traseolide. This odour tended to be very weak and was replaced on the perfumers' strip daily to try and maintain iso-intensity with the other odorants. This attempt may not have been entirely successful, or the high incidence of specific anosmia to this compound may have affected this finding (J.Behan, 1992 personal communication).

Another factor that may have contributed to differences in the rating scales for all odorants is the different interpretation that different subjects' place on the meaning of the words: pleasantness, strength and familiarity. For instance, regarding the pleasantness scale, are their judgements strictly relative to the rest of the odour group, or with their memories of how pleasant they remember other odours to be ? For familiarity, do they know the odour to the extent that they can name it or remember it from somewhere, or do they recognise the odour as being one that they were presented with earlier that day?

The Pearson correlation coefficients matrix given in Table 1.6.2 below shows that there are many strong relationships between strength, pleasantness and the familiarity of the odorants.

Table 1.6.2. Correlation coefficients for each odour for each psychometric dimension.

Odour	Pleasant/Strength	Pleasant/Familiar	Strength/Familiar
Blue Diamond	0.04	0.58***	0.44**
Yellow Topaz	0.16	0.33 *	0.44**
Green Emerald	0.10	0.47 **	0.61 ***
Linalyl. Acetate	0.13	0.47 **	0.36 *
Golden Amber	-0.16	0.24	0.09
Pink Quartz	0.20	0.48 **	0.25
Imperial Jade	0.17	0.43 **	0.45 **
Traseolide	0.56 ***	0.66 ***	0.47 ***
Red Ruby	0.02	0.27	0.51 ***
IVA	-0.51 ***	0.15	0.16
Purple Amethyst	-0.02	0.63 ***	0.28

Key to symbols : *$p < 0.05$ **$p < 0.01$ ***$p < 0.001$

It can be seen from Table 1.6.2, that the dimensions of familiarity/pleasantness and familiarity/strength are often significantly correlated. Thus, for an odour where these correlations are high, a subject finding the odour pleasant is more likely to rate it as familiar, as opposed to unfamiliar. Similarly, if there is a strong correlation between the dimensions of strength and familiarity, a subject rating an odour as weak is more likely to rate the same odorant as unfamiliar. It must be remembered here that these results apply to only this subject group and a particular structuring of the data was not expected.

Tables 1.6.3 & 4 below show the mean subject rating (in descending order of magnitude) on each of the dimensions for all odorants, except androstenone, by sex :

Table 1.6.3. Mean subject ratings for females on each psychometric dimension.(n=26)

Note: The first number in brackets indicates the mean rating for that odour for that dimension. The second figure indicates the rank order of that odorant on that dimension. Standard deviations are given in italics.

Female

Odour	Strength	Pleasantness	Familiarity
IVA	(8.0) (1) *2.3*	(0.9) (11) *1.3*	(6.5) (6) *3.1*
B. D	(7.7) (2) *2.1*	(6.4) (5) *2.3*	(6.5) (5) *2.5*
G. A	(7.6) (3) *1.5*	(6.6) (4) *2.1*	(6.7) (2) *2.5*
L. A	(7.6) (4) *3.0*	(6.2) (7) *2.7*	(7.0) (1) *2.7*
G. E	(7.3) (5) *1.9*	(6.7) (3) *2.5*	(6.3) (7) *2.6*
R. R	(7.3) (6) *2.1*	(5.2) (10) *2.7*	(5.3) (10) *3.1*
I. J	(7.3) (7) *2.3*	(5.5) (9) *2.7*	(6.1) (8) *2.6*
P. A	(7.14) (8) *1.7*	(5.6) (8) *2.6*	(5.6) (9) *2.5*
P. Q	(5.9) (9) *2.4*	(7.2) (1) *2.0*	(6.7) (3) *2.6*
Y. T	(5.3) (10) *2.7*	(7.2) (2) *1.6*	(6.6) (4) *2.3*
Trase.	(4.1) (11) *2.9*	(6.3) (6) *2.6*	(4.9) (11) *3.0*

Table 1.6.4 Mean subject ratings for males on each psychometric dimension.(n=12)

Note: The first number in brackets indicates the mean rating for that odour for that dimension. The second figure indicates the rank order of that odorant on that dimension. Standard deviations are given in italics.

Male

Odour	Strength		Pleasantness		Familiarity	
IVA	(8.4) (1)	*2.5*	(0.6) (11)	*1.1*	(7.4) (1)	*2.6*
G. A	(7.7) (2)	*1.5*	(6.8) (4)	*2.2*	(6.5) (4)	*3.1*
G. E	(7.1) (3)	*1.6*	(6.6) (5)	*2.3*	(6.3) (5)	*1.8*
R. R	(7.0) (4)	*1.6*	(6.4) (7)	*2.1*	(5.7) (8)	*2.0*
P. A	(6.7) (5)	*1.9*	(5.2) (8)	*2.6*	(5.7) (7)	*2.4*
I. J	(6.6) (6)	*1.8*	(5.3) (10)	*2.3*	(5.3) (11)	*2.5*
B. D	(6.4) (7)	*2.4*	(7.1) (2)	*1.7*	(7.2) (2)	*2.2*
L. A	(6.3) (8)	*3.4*	(5.8) (9)	*2.8*	(5.5) (9)	*3.3*
P. Q	(6.2) (9)	*2.0*	(7.5)(1)	*2.4*	(6.2) (6)	*2.5*
Y. T	(5.9) (10)	*2.6*	(6.9) (3)	*2.2*	(6.6) (3)	*2.0*
Trase.	(2.6) (11)	*2.8*	(6.7) (6)	*3.0*	(5.4) (10)	*3.6*

An overall t-test of male and female ratings showed no significant difference on any of the dimensions. The same was true for all of the individual odour comparisons. The reputed superior olfactory acuity of females was not demonstrated in this experiment, but Table 1.6.5 below, shows that women overall rate odours as stronger than males. It must be remembered however, that these odours were at suprathreshold levels which would have influenced this result by producing a ceiling effect. A finding that females may rate the fine fragrances as more familiar because of their postulated wider experience in this

area may have been expected and is supported, as they rate higher overall for familiarity. As can be seen from the table males rate higher overall for pleasantness, a plausible reason for this perhaps being their less strict criteria for an odour to meet to be judged pleasant. Females may expect more of an odour in this respect because in general females have a history of choosing fragrances for themselves.

Table 1.6.5 T-test results between females & males on each psychometric dimension.

Standard deviations are given in italics.

Strength	Female = 6.8 *(2.1)*	
	Male = 6.5 *(1.5)*	p=0.155
Pleasantness	Female = 5.8 *(2.7)*	
	Male = 6.0 *(2.1)*	p=0.516
Familiarity	Female = 6.3 *(3.1)*	
	Male = 6.2 *(2.0)*	p=0.874

T-tests were also performed to discover any significant differences in the mean ratings between: smokers vs non-smokers (smokers were defined as those subjects smoking at least one cigarette per day); those subjects menstruating. It would be expected that smokers and menstruating women may have lower acuity and thus rate odours as being weaker. Significant results are shown below in Table 1.6.6:

Table 1.6.6 Significant differences between smokers and non-smokers on the psychometric dimensions

Smoking (n=17) vs Non- Smoking (n=21) SD=italics

Overall

Strength	Non-smokers	=7.3 *(3.4)*	
	Smokers	=6.2 *(3.5)*	$p < 0.000$
Pleasantness	Non-smokers	=6.4 *(2.4)*	
	Smokers	=5.7 *(3.4)*	$p < 0.001$
Familiarity	Non-smokers	=6.7 *(2.3)*	
	Smokers	=6.1 *(3.4)*	$p < 0.05$

By Odour

Linalyl Acetate	Strength	Non-smokers	=8.4	*1.8*	
		Smokers	=5.8	*3.8*	$p < 0.01$
Blue Diamond	Strength	Non-smokers	=8.2	*1.4*	
		Smokers	=6.3	*2.7*	$p < 0.01$
Imperial Jade	Familiarity	Non-smokers	=6.7	*2.2*	
		Smokers	=4.9	*2.7*	$p < 0.05$

The table above shows clearly that smokers rate odours significantly lower than non-smokers on each of the three dimensions. The reason for this may be that because of their reduced acuity, they tend to rate lower on the other two dimensions. This would support the reduced acuity findings in the literature, reported above.

Table 1.6.7. Significant differences between those menstruating and those not on the psychometric dimensions

Note: Interestingly, the overall result remained the same even if the male scores were included in the non-menstruating group.

Menstruation (n=9) vs Non-menstruation (n=29) SD=italics

Overall

Familiarity	Non-Menstruation	=6.4 *(3.1)*	
	Menstruating	=5.5 *(3.3)*	$p < 0.01$

By Odour

Golden Amber	Familiarity	Menstruating	=7.8	*1.4*	
		Non menses	=6.3	*2.9*	$p < 0.05$
Purple Amethyst	Familiarity	Non menses	=6.1	*2.5*	
		Menstruating	=4.3	*1.9*	$p < 0.05$

It would seem that menstruation has a significant effect on the familiarity ratings. Why this should be so is not at all clear, but the particular odours above are two of the "heaviest" included in the sample. Perhaps hormonal and mucosal changes affect the perception of these odours causing them to be less familiar. The possibility remains however that this result is rather artifactual considering the number of significance tests performed on the data, but it does seem generally supportive of the literature.

Analysis of the psychometric data collected in the second main experimental study.

Subjects in the second part of this study numbered eleven. The psychometric rating procedure remained identical to that in the first testing session. The odours rated included five from the set used in the first testing period, two dilutions of one of these

odorants (Blue Diamond) and five new odorants. See Appendix 2 for the odour descriptors.

Apart from the two dilutions, the odorants were at 20% in dipropylene glycol. The two dilutions of Blue Diamond were at 1% and 0.25% concentration. The method of rating the odours remained the same as in the first testing session. Table 1.6.8 below, shows the mean subject rating (in descending order of magnitude) on each of the dimensions for all odorants.

Table 1.6.8 Mean subject rating on each psychometric dimension one year later (n=11)

Notes: The first number in brackets indicates the mean rating for that odour for that dimension. The second figure indicates the rank order of that odorant on that dimension. Standard deviations are given in italics. Blue Diamond at 0.25 % was only detected by 2 female subjects and so was not included in the above table.

Odour	Strength		Pleasantness		Familiarity	
G. A	(8.0) (1)	*1.0*	(5.9) (10)	*1.2*	(6.0) (8)	*2.7*
R. R	(7.7) (2)	*2.0*	(6.0) (8)	*2.4*	(6.0) (7)	*3.2*
9135	(7.4) (3)	*2.2*	(6.4) (5)	*1.4*	(6.1) (6)	*2.6*
9152	(7.2) (4)	*2.9*	(6.3) (7)	*2.7*	(6.3) (5)	*2.9*
9116	(7.2) (5)	*1.5*	(6.5) (4)	*1.6*	(7.0) (1)	*2.2*
B. D20%	(7.0) (6)	*2.0*	(5.8) (11)	*1.9*	(6.8) (3)	*2.0*
P. Q	(6.6) (7)	*2.3*	(6.4) (6)	*2.5*	(6.3) (4)	*2.5*
9105	(6.5) (8)	*2.0*	(6.6) (3)	*1.7*	(5.6) (10)	*2.2*
Y. T	(6.3) (9)	*2.9*	(6.7) (1)	*1.6*	(5.9) (9)	*2.9*
9178	(6.1) (10)	*2.9*	(6.7) (2)	*1.3*	(6.9) (2)	*2.9*
B. D1%	(1.6) (11)	*1.7*	(5.9) (9)	*1.2*	(2.7) (11)	*2.3*

This table again shows the distribution of scores within this particular subject group. This is useful for purposes of analysing the physiological data, but is not anticipated to show any particular structure. Nor is it expected to show any relation to the earlier table.

Table 1.6.9 below, shows the correlations for all of the dimensions for all of the odorants.

Table 1.6.9 Correlation coefficients for each odour for each psychometric dimension one year later.

Odour	Pleasant/Strength	Pleasant/Familiar	Strength/Familiar
9105	0.51	0.73***	0.05
9116	0.27	0.77**	0.05
9152	0.20	0.80**	0.15
9178	0.51	0.16	0.41
9135	0.85***	0.64*	0.58
Red Ruby	0.16	0.84***	0.08
P.Quartz	0.25	0.44	0.51
Golden Amber	0.21	0.19	0.61*
Y.Topaz	0.83**	0.97***	0.85***
B Diamond 20%	0.16	0.62*	0.40
B.Diamond 1%	0.78*	0.27	0.45

Key to symbols *p<0.05 **p<0.01 ***p<0.001

The Pearson correlation coefficients matrix above shows a less strong relationship between strength, pleasantness and familiarity than that contained in the first part of this study, in Table 1.6.2. and this may be a consequence of the use of different odours. Also, there is no reason for this table to show a similar pattern to the first.

Tables 1.6.10 & 11 below, show the mean subject rating (in descending order of magnitude) on each of the dimensions for all odorants by sex :

Table 1.6.10 Mean rating on each psychometric dimension for all odours for females one year later (n=11)

Note: The first number in brackets indicates the mean rating for that odour for that dimension. The second figure indicates the rank order of that odorant on that dimension. Standard deviations are given in italics.

Odour	Strength		Pleasantness		Familiarity	
R. R	(8.4) (1)	*1.8*	(5.4) (8)	*3.0*	(5.8) (9)	*3.5*
G. A	(8.3) (2)	*1.0*	(5.3) (10)	*1.1*	(6.5) (3)	*1.8*
B.D20%	(7.7) (3)	*1.1*	(4.9) (11)	*1.7*	6.4) (4)	*2.0*
9152	(7.7) (4)	*3.4*	(5.5) (7)	*3.2*	(6.1) (6)	*2.7*
9116	(7.1) (5)	*1.9*	(6.2) (3)	*2.1*	(6.7) (1)	*2.7*
9135	(6.9) (6)	*2.8*	(6.1) (4)	*1.7*	(5.8) (8)	*2.8*
P. Q	(6.7) (7)	*2.6*	(7.1) (1)	*1.8*	(6.1) (5)	*2.5*
Y. T	(6.7) (8)	*3.4*	(6.6) (2)	*1.6*	(5.9) (7)	*2.7*
9105	(6.6) (9)	*2.0*	(5.7) (6)	*1.8*	(5.2) (10)	*2.1*
9178	(6.3) (10)	*3.3*	(6.0) (5)	*1.1*	(6.5) (2)	*1.3*
B.D.1%	(0.8) (11)	*1.0*	(5.3) (9)	*1.0*	(2.5) (11)	*1.7*

Table 1.6.11. Mean rating on each dimension for all odours for males one year later (n=5)

Note: The first number in brackets indicates the mean rating for that odour for that dimension. The second figure indicates the rank order of that odorant on that dimension. Standard deviations are given in italics.

Odour	Strength		Pleasantness		Familiarity	
9135	(7.9) (1)	*1.0*	(6.8) (8)	*1.1*	(6.4) (5)	*2.7*
G. A	(7.6) (2)	*1.4*	(6.6) (10)	*1.0*	(5.4) (10)	*3.6*
9116	(7.3) (3)	*1.2*	(6.8) (7)	*1.0*	(7.4) (1)	*1.6*
R. R	(6.9) (4)	*2.0*	(6.7) (9)	*1.6*	(6.3) (6)	*3.2*
9152	(6.8) (5)	*2.5*	(7.3) (4)	*1.6*	(6.7) (3)	*3.4*
P. Q	(6.5) (6)	*2.2*	(5.6) (11)	*3.1*	(6.6) (4)	*2.7*
9105	(6.3) (7)	*2.4*	(7.6) (1)	*1.0*	(6.2) (7)	*2.4*
B.D20%	(6.2) (8)	*2.6*	(6.9) (5)	*1.5*	(7.2)(2)	*2.0*
9178	(6.0) (9)	*2.7*	(7.5) (2)	*1.0*	(5.9) (9)	*3.4*
Y. T	(5.9) (10)	*2.5*	(6.9) (6)	*1.7*	(5.9) (8)	*3.4*
B.D1%	(3.7) (11)	*1.8*	(7.5) (3)	*0.3*	(3.2) (11)	*4.6*

T-tests revealed that there were significant differences on certain dimensions for some odorants between female and male subjects and these results are shown below:

Table 1.6.12. Significant differences between females and males on the psychometric dimensions one year later

Standard deviations are given in italics.

Overall

Pleasantness	Male	=6.9 *(2.1)*	
	Female	=5.9 *(1.5)*	$p < 0.001$

By Odour

B.D1%	Strength	Male	=3.7	*1.8*	
		Female	= 0.8	*1.0*	$p < 0.05$
B.D1%	Pleasantness	Male	=7.5	*0.3*	
		Female	=5.3	*1.0*	$p < 0.01$
Golden Amber	Pleasantness	Male	=6.6	*1.0*	
		Female	=5.3	*1.1*	$p < 0.05$
9178	Pleasantness	Male	=7.5	*1.0*	
		Female	=6.1	*1.1*	$p < 0.05$

Males again rate higher for pleasantness than females and the result is significant. On this occasion males rate the odours as stronger than the females and they also rate them as being more familiar. This modifies the results gained in the first part of this experiment and it is clear that more research is necessary in this area to tease out all of the possible contributing factors to the observed gender differences in odour perception.

Unfortunately it was not possible to test the effects of smoking or menstruation in this group because of the lack of comparable groups, i.e., there were no smokers and no menstruating women.

Analysis of androstenone data collected in the first main experimental study

Introduction

Androstenone was not included in the above analysis because responses to this particular odour fall into three distinct categories. Approximately 50% of the population are anosmic to it (Labows & Wysocki 1984) and of the other half of the population, approximately 25% rate it as unpleasant, 25% as pleasant. The table below shows the distribution of groups within the responses to androstenone in this subject group.

Table 1.6.13 Distribution of groups by response to Androstenone.(n=38)

	Anosmic	Unpleasant	Pleasant
Female	10	11	5
Male	5	5	2
Menses	2	5	2
N/Menses	8	6	3
Smokers	7	8	2
N/Smokers	8	8	5

In the above table it can be seen that 39% of subjects are anosmic to androstenone, a good approximation to the expected result considering the sample size. No further obvious conclusions can be drawn from this table, except to say that smoking behaviour and menstruation do not appear to have any significant affects on the perception of androstenone as expected. The division of the psychometric response into the three categories, listed above, probably preclude the confounding variables of gender or smoking habits.

Androstenone provides an effective test for the data analysis programme, in that the responses are so clearly defined psychometrically into the three distinct groups. If

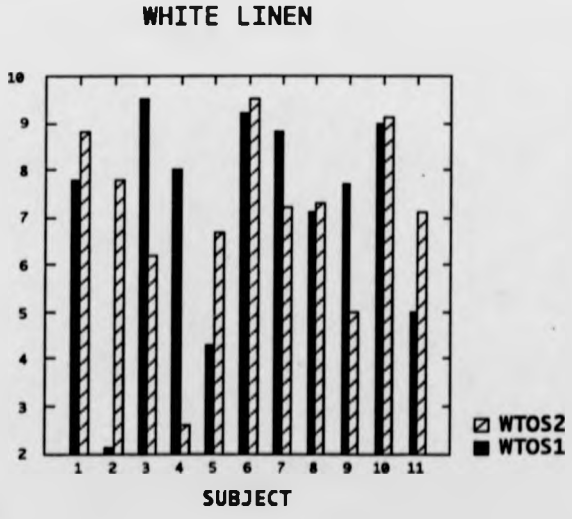
psychometric information is represented in the EEG response to odours then androstenone data is the obvious place to start looking for EEG differences.

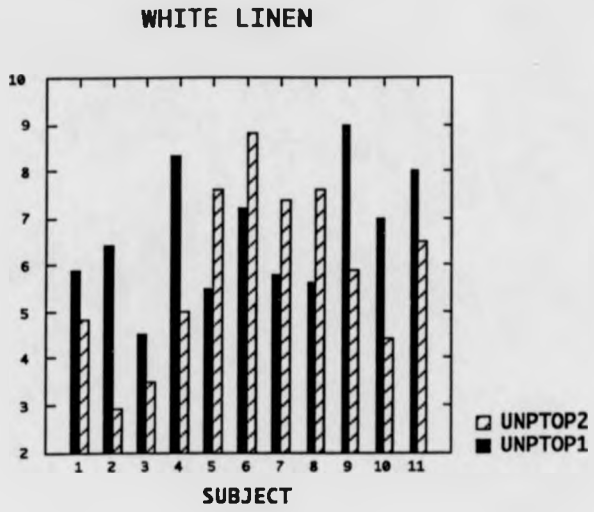
Analysis of the longitudinal relationship between the psychometric data collected in the first and second main experimental studies

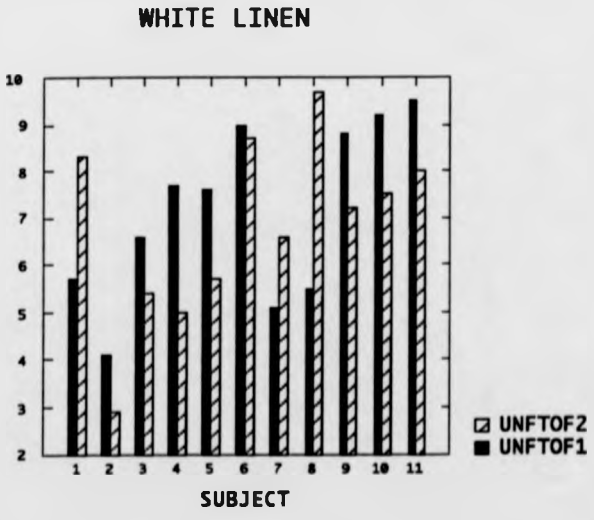
This section of the report examines the longitudinal relationship between the ratings of five odorants made by eleven subjects, and their ratings of the same odorants one year later. To recap, the odours were, Red Ruby, Yellow Topaz, Blue Diamond (20%), Green Emerald and Pink Quartz. Appendix 5 (longitudinal psychometric graphs) contains a series of graphs that demonstrate the changes that have occurred over time for each of the eleven subjects, on each dimension for each odorant. Examples of the graphs for Blue Diamond are shown below, in Figure 1.6.1

The key for the graphs is:

WTOS	= Strength	1= first testing session (black)
UNPTOP	=Pleasantness	2=second testing session one year later. (shaded)
UNFTOF	=Familiarity	Vertices show the rating points (1-10)







Group means for the first and second tests are shown below in Table 1.6.14:

Table 1.6.14. Group means for the first and second psychometric tests.

Standard deviations are given in italics.

Odour	Test One (n=38)			Test Two (n=11)		
	w-s	unp-p	unf-f	w-s	unp-p	unf-f
R R	7.3 *(2.1)*	5.6 *(2.7)*	5.4 *(3.1)*	7.8 *(1.6)*	6.0 *(2.1)*	6.1 *(2.0)*
B.D	7.3 *(2.1)*	6.7 *(2.3)*	6.8 *(2.5)*	7.0 *(2.4)*	5.9 *(1.7)*	6.8 *(2.2)*
P.Q	6.1 *(2.4)*	7.4 *(2.0)*	6.6 *(2.6)*	6.7 *(2.0)*	6.4 *(2.4)*	6.4 *(2.5)*
G.A	7.7 *(1.5)*	6.7 *(2.1)*	6.7 *(2.5)*	8.0 *(1.5)*	5.9 *(2.2)*	6.0 *(3.0)*
Y.T	5.6 *(2.7)*	7.2 *(1.6)*	6.7 *(2.3)*	6.4 *(2.6)*	6.8 *(2.2)*	5.9 *(2.0)*

Key: w-s = weakness (0) to strength (10)unp-p = unpleasant (0) to pleasant (10)

unf-f = unfamiliar (0) to familiar (10)

There are no significant differences for any of the odours individually. Despite the fact that Red Ruby was found to be more pleasant by the group on the second occasion it was rated, only the dimension of pleasantness altered significantly over time ($p < 0.05$) for the group, with the individual odours Yellow Topaz, Blue Diamond, Pink Quartz and Green Emerald being rated as less pleasant the second time around.

Individual subject ratings were also remarkably stable over time. Only two subjects rated the odours as significantly stronger on the second test, while two subjects rated the odours significantly differently for familiarity, one subject finding the odours more familiar on the second test, and another finding them less familiar.

There were some changes in the correlations between the dimensions of weakness, pleasantness and familiarity for the five odorants.

Blue Diamond on the second occasion was no longer very strongly correlated for pleasantness/familiarity and the strong correlation between strength/familiarity has disappeared. For Golden Amber strength and familiarity become significantly correlated, and pleasant/strength are no longer negatively correlated. Red Ruby is no longer correlated very strongly on strength/familiarity, but has become very strongly correlated on the pleasant/familiar dimension. Pink Quartz lost the strong correlation between pleasant and familiar. Yellow Topaz became more strongly correlated on all dimensions.

The conclusion is that no major differences exist for the group from one test to the next. However, as was the case for androstenone, subjects who show large differences in their rating behaviour from one session to the next could be a good place to start any data analysis of the intra-subject data.

Summary and discussion

The first point of interest in the report is the difficulty of controlling the intensity of the different odours. It may be expected that the strength dimension would show the most consistency within the group but, although the odours were virtually iso-intense over the group, there were wide individual variations. As all odorants were tested for iso-intensity both by Quest and in the Warwick Laboratory, it would seem that the wide variation is probably because of individual physiology, varying mucus levels, sniff strength and a wide variation in the interpretation of the "strength" dimension.

The finding that females and non-smokers show an increased olfactory acuity compared to males and to smokers respectively is demonstrated clearly in this research and supported by the literature. However the results that show significant differences between menstruating subjects, non-menstruating subjects are difficult to interpret.

The long term stability of the rating behaviour of most subjects over time gives no extra clue to analysing the data, but those subjects who have rated the odours as significantly different for each occasion may have EEG differences that reflect this.

The psychometric results provide information that will be useful in the analysis of the main EEG data set. In particular, the EEG records for those odours that were psychometrically the most distinctive will be chosen for inclusion in the main analysis procedures. In this way it may be possible to identify topographical features evident in the EEG data that reflect perceptual attributes of the odours. The EEG records for Pink Quartz have been included in the samples chosen for EEG data analysis because it is the odour that has been rated as the most pleasant by both males and females. Similarly, the EEG records for IVA have been chosen, because it was consistently rated as the most unpleasant odour by both males and females. EEG records for Polo have been included as this was the perfume rated as being most unpleasant.

Blue Diamond EEG records have been included because this odour has the highest psychometric rating for familiarity, and Traseolide has been included because it has the lowest rating on this dimension. Perhaps the most important odour for studying the possible perceptual differences on the topographical EEG is androstenone. There is a distinct and well known division of the perceptual reaction to this odour. Approximately 50% of the population are anosmic to it, of the remaining half, 25% find it pleasant, 25% find it unpleasant. However, even though some of the analyses of the data will concentrate on only these odours, the main analysis technique initially will be a feature detection method to further reduce the amount of data to be anaysed.

Results 1

Reliability Report, a visual analysis of the data

The central problem of the present research programme has been to identify and quantify the odour induced change in a large number of EEG records. Several problems were immediately apparent: individual EEG variability was very high; it was not known how each of the very different odours may exert their effect (s); and it was not reliably known where on the cortex these effects may appear. Some early evidence suggested a grouping of electrodes towards the parietal/occipital area of the cortex (Van Toller, Hotson & Kendal-Reed, 1992) but it was decided that the analysis of data in this study would not concentrate exclusively on this area because of the lack of supporting evidence.

An early attempt to gain an understanding of the structure of the EEG power data was to present it in a different format. The colour maps are useful when making clinical decisions about individual or small group patient data, but when it comes to making complex and multiple spatio-temporal comparisons across many subjects colour maps add to the confusion rather than reducing it. The graphical representation of the data was seen as a preferrable method of data display for the following reasons: it was possible using the graphs to present a whole series of data containing upto fifteen frames, that could be scanned at a glance, using maps would have involved one map for each frame. The maps would have the added variables of colour and anatomical location of change(s) for the observer to take into account. The study was designed to see if gross changes in the EEG occured after the presentation of an odour, and to what extent odour records and blank records could be discriminated within subjects. At this stage the question was not where this change may occur in terms of the location of the electrode(s). Graphical representation of the data allowed the observer to immediately perceive the flow of the data and scan for discontinuities. Furthermore, the fact that a whole series of maps could be compressed into a single graph meant that more data could be analysed in this way. Considering the relatively limited number of variables being observed per individual record, a graphical method was seen as invaluable. Such methods permit a visual

examination of the distribution of the data and can suggest which records are noteworthy for particular features, such as dispertion or closure. The dimensionality of the colour maps was seen as impractical for the requirements of this study.

For these reasons entire data sets for six subjects (3 females and 3 males), all 14 odour trials (in all wavebands), for the morning and afternoon, were downloaded from the brain imager (see Appendix 4 for details). Androstenone trials for all subjects, morning and afternoon were also downloaded. This data, in the form of matrices (see Appendix 2.4.2, for an example frame of data) was then run through a computer programme, developed by Kendal-Reed & Halstead (Kendal-Reed, 1990: Vol. 2: 24 & 34-42) on the University's mainframe. The programme presented the data in the form of time series graphs, see Appendix 2.5.1 (power data in graphical form) with the x axis representing time and the y axis representing power.

The author then spent considerable time trying to discriminate any recognisable and replicable patterns in the data. To do this meant that the graphs had to be displayed and periodically rearranged in terms of subject, odour, time of day, waveband and psychometric response. It became increasingly clear that there appeared to be no obvious patterns emerging. This being the case, even knowing the point at which the odour had been presented, and indeed even between odour and blank records. A more extensive study was undertaken to examine the responses of naive observers. The graphs for the following study were created using a programme written for the author by Dr. Collis of the Psychology Department. The only difference to the above programme was that it could be implemented on the computer used by the author.

A reliability study was implemented to answer some basic questions about the nature of the data. In particular, could observers unfamiliar with the nature of the research reliably detect changes in the overall pattern of a large number of EEG graphs indicating the presentation of an odour? In other words, do the odours affect the EEGs' to the extent that an untrained observer can detect the point at which the "resting" EEG changes to one where a sensory/cognitive event has occurred ? It has been said that visual analysis of

EEG records for discontinuities is the "gold standard" and the human pattern recognition system is acknowledged to be without artificial comparison (Duffy, 1989).

The present study was concerned firstly with observers' ability to detect a change in underlying pattern indicating that an odour may have been presented. So in terms of the signal detection paradigm, the observer's task was to identify a change in pattern, this being the equivalent of a signal, in a signal detection paradigm. The task omitted however, the assignment of probability or certainty levels because the experiment was not designed as a classical signal detection task. The reasons for this were that the experimenter could not vary the ratio of signal to noise, the interest lay not in the criterion the observers used but in if they could differentiate between an odour and a no-odour record. It was not assumed that each odour would produce the same change in the EEG graph and indeed the observers were instructed not to become fixated on a particular type of change but to consider each graph on its own merits. It was expected that the high level of inter-subject variability would make this an extremely difficult task to accomplish above chance levels. However a further hypothesis, that observers would be more successful when considering several EEG graphs from a single subject was also tested. The rationale behind this being that if there is such a thing as a "baseline" or "resting" EEG, then comparing intra-subject records would maximise the potential for detecting the overall pattern for each subject and hence where that pattern has been interrupted. The difficulties relating to the high inter-subject variability would then be reduced to a minimum.

A further question, related to the place on the EEG record where observers may identify a change in overall pattern, was also considered. Observers may identify changes but if these are not related to the period of odour presentation then it becomes clear that the presentation of an odour does not affect the EEG significantly enough, and it does not produce a large enough signal to be identified in the on-going noise of a subject's EEG.

The signal that the observers would be expected to look for is a change in the power variability in an EEG record, either more or less synchrony depending on their opinion of

the overall pattern. Individual observers were able to decide if the positive identification of a change was based on the activity of a single electrode or more than one. It would seem that a gestalt interpretation was most suitable in this instance based on the perception of proximity, similarity, closure, common destiny and common movement.

The EEG graphs used for the group study were chosen because of their unusual or distinctive nature in the psychometric rating study. Iso-valeric acid, linalyl acetate, and traseolide are described in Appendix 2. Three fragrances were chosen, those identified in Howells (1992) that were set apart from the remaining fragrances, Imperial Jade, Blue Diamond and Pink Quartz. In the psychometric report these odours were identified as having important differences. Pink Quartz was rated as the most pleasant odour, whilst Imperial Jade was the most unpleasant perfume, and IVA the most unpleasant odour overall. Blue Diamond was rated as the most familiar odour, whilst Traseolide was the most unfamiliar. In addition, two blanks provided the necessary contrast to the odour records. It would be relatively meaningless to to have a possible response of "yes" to a signal plus noise record unless the possibility of a "yes" response to a noise only record exists. The odour records were from the first main experimental testing session, collected in the morning and the afternoon. Because of the sheer volume of graphs that would result from using all of the wavebands, only the alpha waveband was chosen, mainly as the postulated odour effects on the EEG have been demonstrated here (Lorig, 1989, 1991; Van Toller et al, 1992).

Method

Subjects

Thirty-two observers were recruited. Four of these were familiar with the main study and formed an "expert" group.

Materials

Task 1

Fifteen sets of odour records were prepared. Each set contained from twenty-six to thirty-three individual EEG graphs, all of the same odour or blank. Those records that were contaminated by artifact were not used. The sets were; IVA, Trasolide, Linalyl Acetate, Blue Diamond, Imperial Jade, Pink Quartz, Blank 1, and Blank 2. Both am and pm records were printed out for all of these except for Blank 2, which contains only pm records.

Task 2

Most of the fifteen sets of EEG graphs above were photocopied and sorted into thirty-five sets of individual EEG graphs. Some records used for Task 1 however were not used in Task 2 as a minimum of three records per individual was thought necessary. Thus, each set in this instance contained an individual's EEG response to all odours and blanks. The photocopies and the original graphs were then distributed randomly throughout the two groups to ensure that any effect of different style of presentation of the stimuli was reduced to a minimum.

Procedure

In Task 1, the subjects were to sort through only four sets of a possible fifteen, to keep the task at manageable levels. As a result of this the sets were randomised to ensure that each would be sorted by an equal number of observers. Each observer received three odour sets and one blank set.

Half of the observers (n=16) were given Task 1 first, the remainder of the observers were given Task 2 first. This was to balance out the training effect that may have occurred over the course of the categorisation task, and to counter any effects of fatigue or boredom.

Task 1

Each observer's pile of EEG graphs consisted of three odour (noise plus signal) sets and one blank set (noise only). They were asked to look at each EEG record and to decide if over the course of the trial there was a change in underlying pattern, that may indicate the presentation of an odour. They were not at any time informed as to where they could expect such a change to occur, nor what such a change may look like. The EEG graphs were shuffled before and after presentation to each observer. Their task was to sort the pile into two groups "yes, there is a change", or "no, there is no change." The observers were told not to expect an equal split into two groups but that the stimuli they were rating could be all "yes" or all "no." There was no time restriction and the experimenter gave no feedback on the decisions.

Task 2

The observer was asked to look at each set of individuals' EEG graphs and indicate for each one if there was a change in underlying pattern, as above. This time however, if there was a change they were asked to specify at which points they considered it to be happening. Again, there was no time restriction and no feedback from the experimenter.

Results

The chosen statistic for this analysis was chi-square which helps to determine whether a systematic relationship occurs between two variables. However, caution must be exercised when the number of cases is large because then even tiny deviations will generate a significant chi-square.

Task 1

Table 1.6.15 shows a frequency count of the categories found when the EEG graphs were sorted by group. The percentages are also given.

Table 1.6.15 Reliability study : frequency count and percentage of change by odour

	No odour	odour
No change	597 (16%)	1630 (43%)
Change	339 (9%)	1226 (32%)

A Chi-squared test gave a value of 13.1 (df = 1, $p < 0.000$). However, the large number of this sample n=3,792 may have affected this result. The *phi* value for this result was 0.06 showing a very weak relationship between the variables and one that suggests that the significant chi-squared result was an artifact produced by the large number of cases.

Furthermore a Cohen's Kappa result of 0.05 shows a very poor agreement between the observers which reinforces the view that the large number of cases has produced this significant effect.

The table below shows that there is no significant difference between the correct categorisation between those EEG graphs obtained in the morning versus those taken in the afternoon.

Table 1.6.16 Percentages of correct categorisation of the reliability data in the morning and in the afternoon

	No odour	Odour
AM	65 %	41 %
PM	63 %	43 %

Additionally, no one odour set was correctly categorised significantly above or below chance levels.

Task 2

Table 1.6.17 shows a frequency count and percentage calculation of the categories found when the EEG graphs were sorted by individual.

Table 1.6.17 Reliability study: frequency count and percentage of change by odour

	No odour	Odour
No change	1517 (11%)	5785 (41%)
Change	1203 (8%)	5639 (40 %)

The chi-squared value was 23.2 (df=1, p<0.000). However the very large number of cases in the table cells n= 14,144 and the *phi* value of 0.04 again suggests that this result is an artifact produced by the large numbers and this is supported by the Cohen's Kappa measure of inter-rater agreement of 0.03, suggesting there is little agreement between observers.

The "expert group" percentage results are shown below in Table 1.6.18

Table 1.6.18 Reliability study: percentages of change by odour for the expert group

	No odour	Odour
No change	11 %	40 %
Change	7 %	42 %

The above table shows that the "experts" (researchers working with the same experimental paradigm) who were aware of the nature of the experiment and the point of presentation of the odour, performed little better than naive observers. This demonstrates the difficulty of this task. Furthermore, it is an indication of the lack of a clear "odour signal" through the noise of the EEG that can be easily distinguished. As a consequence of apparently subtle effects, traditional statistics will have difficulty with such data.

Again, there were no significant differences between the correct categorisation of the EEG graphs obtained in the morning versus those taken in the afternoon. Also, no one individual EEG set was more than 75 % correctly categorised when an odour record was presented, the highest total being 72 %. Given below is the distribution of percentage correct categorisations for odour graphs given to individual EEG sets.

Table 1.6.19 Distribution of percentage correct categorisation for individual odour sets in the reliability study

10 - 20 % =	3	40 - 50 % =	5
20 - 30 % =	6	50 - 60 % =	11
30 - 40 % =	10	60 - 70 % =	0
	70 - 80 % =1		

Using the results categorised using sets of an individuals' EEG it was possible to break the results down further for effects of gender. If males and females do react differently as groups to an odour presentation, this may be reflected in their EEG graphs.

Table 1.6.20 Percentages of cell categorisation for female and male records in the reliability study

	Female (%)		Male (%)	
	No odour	Odour	No odour	Odour
Change	11	42	7	41
No change	8	39	8	44

As can be seen from the above table, there are no effects based on the gender of the subject. This finding suggests that analysing male and female records separately may not be necessary. It appears that the first aim of this thesis, that of demonstrating a difference between the no-odour condition and the odour condition, will be problematic, without the added effects of gender.

Discussion

The main objective of the present study was to determine if naive observers could detect a change in underlying pattern in a series of EEG graphs, related to the presentation of an odour. The results suggest that this is not possible. Not only is the task performed badly by naive observers but also by the group of "experts," this is despite the fact that they are familiar with the methodology, they know exactly where to look for an effect, although not exactly what this effect may be. The first hypothesis, that the sorting task would be very difficult when the EEG graphs were presented by type of odour was borne out. The observers as a group were performing at chance levels. This is probably because of the degree of variation present in the individual EEG graphs. Also, an odour may not exert the same effect on individuals depending on a variety of different factors, including prior EEG state, physiological state, cognitive and or sensory reactions to the odours, previous experience with the odour etc. This result would suggest that any effect exerted by the odours chosen for this study are not distinct enough to be detected in this way. Either the effects are too subtle to be detected by this sort of rating exercise or the information contained in the odour signal reaching the cortex is too weak or degraded to be reliably de-coded.

The results are in fact worse than the above tables suggest. Many observers' correctly classified the graphs into the odour (something happening) category, but wrongly identified the point of change. That is, the graph was that of an odour but the point of identified change was not consistent with the point at which an odour had been presented.

It was also obvious that the intra-subject records could not be reliably sorted into odour and no-odour groups. This strongly suggests that subjects' EEG graphs demonstrate no "baseline" which can be used to gauge the change occuring with the presentation of an odour. This confirms that any inferential statistical method is likely to have great difficulty in distinguishing the odour part of an EEG record from a non-odour part, even within subjects. The problem is to demonstrate a significant EEG change and one that

occurs with the presentation of an odour. These findings show how subtle the effects of odour on the ongoing EEG are, and further illustrates the need for data reduction before any statistical analysis can take place. Before investigating the effects of different odours on the EEG, which would involve analysis of only the odour frames, the next analysis concentrates on finding a difference in EEG power before and after the presentation of an odour.

CHAPTER SEVEN

Results II

EEG power data analysis - Introduction

At each stage of the following sections it will be made explicit exactly what data sets have been used in the analyses. The Imager produces power data in microvolts, and the data is averaged over a 2.56 second period. Prior to recording the levels of possible artifact were minimised by ensuring good electrode to scalp contacts, low impedance levels, and a visual check on the EEG before recording began. After recording each subject file for each odour trial was checked for artifact. This involved a visual analysis of each frame, undertaken when the data was being downloaded from the Brain Imager. Any unusually high or low values present in a map led to it being discarded. In some cases whole subject trials were discarded as it had been impossible to reduce their impedance levels while testing. It was possible while reviewing the data to display all wavebands simultaneously, enabling a frame deletion if artifact appeared in any waveband. If the frequency components of the artifact appeared outside of the frequency range of the EEG, the problem of artifact deletion became easier. If, however, the artifact appeared within the frequency range of the EEG itself the task became more difficult. Thus, unusual delta activity was looked for that may have indicated movement or eye movement artifact and also excessive drowsiness, and the beta waveband was examined for muscle artifact. Eye movement artifact was looked for in the fontal and occipital leads particularly.

Singular Value Decomposition Analysis

It is important to note that a singular value decomposition analysis (SVD) is mathematically, exactly the same as a principal component analysis. The difference in terminology arises from different academic disciplines not a procedural difference. This analysis was undertaken with the assistance of the Non-Linear Systems Laboratory at the

University of Warwick. Dr. Greg King and Dr. Mark Muldoon provided their advice about the feasibility of a non-linear analysis of the data collected for the study. In their opinion it was impossible to perform any such analysis because of the inadequate length of the time series. With such a short time series it would be impossible to properly characterise the presence or absence of any attractor. Plus, the problems of using multiple lead data have still not been overcome, as discussed in Chapter 4. In effect, to find shifts in the dimensionality of a non-linear time series related to odour would necessitate a complete change of methodology, and this is considered further in the discussion.

The aim was to begin the analysis of the power data with a basic question, namely, is there a difference between the EEG from subjects in a no-odour condition, compared to their EEG in an odour condition ? To achieve this, a singular value decomposition method was employed. For the present analysis the SVD method is being used to determine if the power pattern from subjects in a no-odour state can be differentiated from their odour power pattern, in vector space. Vector coordinates are constructed from a covariance matrix from the no-odour power patterns, and then the same coordinate system is used to try to describe the odour power patterns. If this is not possible, then it is an indication that the odour power patterns are significantly different from the no-odour patterns, in vector space. This analysis forms the necessary first step in a series of analyses to determine the odour vs no-odour differences.

Method

Subjects

Not all of the original 38 subjects' EEG records were used. Because of anomalous power values, the records for 13 subjects in the morning and 12 subjects in the afternoon (not necessarily the same subjects) were discarded, leaving a total of 25 (am) and 26 (pm) subjects to be analysed. Eight complete subjects (i.e., am and pm) were discarded, with 5 subjects' am data discarded and 4 subjects' pm data discarded. This was an intra-subject

study in that it compares the odour and no-odour conditions of the same subject. Separate intra-subject analyses were carried out, for the am and pm data.

Data Files

Singular value decomposition, like a principal component analysis requires large amounts of data if it is to be effective and valid. For this reason, a way had to be found of combining several odour records together, from the same subject. An intra-subject study was considered essential at this point to look at the data more closely, especially in view of the reliability study results which seemed to suggest that there was no way that the odour part of an EEG record could be differentiated from a no-odour part, even within subjects. It was decided that the eight fine fragrances probably formed a more coherent group than any of the other odours, and that the four frames of odour data for each fragrance could be combined into a single "odour matrix" for each subject. The same assumption was made for the five no-odour frames for each of the eight trials, namely that all no-odour frames combined across the eight trials would form a representative "no-odour" matrix, or a "baseline." A comparison of these two datasets should then reveal if the "odour" brain is different from the "no-odour" brain.

Procedure

For each subject, am and pm, their data was read into the programme designed by Dr. Muldoon of the maths department. Each subjects' data was analysed separately. Where both am and pm data were used, these two batches of data were also kept separate.

The power data from the five pre-odour frames were normalised by the mean of those five frames; this was done separately for each electrode and each waveband. Data from the four post-odour frames were similarly normalised by their means.

The first principal component was then extracted from a 5x5 covariance matrix, that summarised the covariance between the five pre-odour frames across the 140 signals (28

electrodes x 5 wavebands). A similar analysis was carried out on the data from the four post-odour frames.

If there is a significant difference between the vector co-ordinates from the pre-odour data and the post-odour data, it would be the case that the odour frames could not be described as the same system that describes the no-odour frames. The results of a series of t-tests performed on the two sets of figures for each subject, for both times of day, are given below.

Results

Table 1. 7.1 T-test results between no-odour principal component and odour principal component for 25 subjects am and 26 subjects pm

Subject	Day	No odour mean	Odour mean	Pooled Variance "t"	Prob. "p"
1	am	74.865	78.067	-0.342	0.734
	pm	64.320	47.371	2.986	0.004**
2	am	111.649	100.004	1.998	0.050*
	pm	76.154	57.775	1.570	0.121
3	am	46.158	41.403	1.438	0.155
4	pm	41.184	43.448	-0.166	0.869
5	am	64.424	62.473	0.801	0.426
	pm	62.021	61.225	0.278	0.782
6	am	45.932	48.840	-0.952	0.345
	pm	48.347	46.836	0.525	0.601
7	am	114.847	108.390	0.749	0.458
	pm	100.968	106.620	-1.130	0.262
8	am	161.763	166.038	-0.345	0.731
	pm	147.849	146.213	0.126	0.900
9	am	56.098	39.646	1.588	0.118
10	am	72.133	65.033	1.092	0.279
	pm	39.693	29.450	1.160	0.250
11	am	86.301	73.253	1.208	0.231

12	am	56.287	44.839	3.152	0.002**
	pm	95.119	95.413	-0.053	0.958
13	am	87.011	83.192	0.900	0.371
	pm	48.628	39.586	1.345	0.183
14	am	42.274	39.153	0.871	0.387
	pm	71.390	65.366	0.348	0.729
15	am	91.620	90.484	0.170	0.866
	pm	66.306	71.429	-0.594	0.554
16	am	48.505	44.296	0.232	0.817
	pm	60.767	55.051	1.024	0.309
17	am	43.767	28.941	1.432	0.157
	pm	126.810	105.884	1.232	0.223
18	am	109.744	107.934	0.416	0.679
	pm	165.722	171.731	-0.776	0.440
19	am	46.924	44.125	0.280	0.780
	pm	64.255	61.753	0.371	0.752
20	pm	72.647	73.096	-0.082	0.935
21	am	91.612	90.975	0.096	0.924
	pm	166.544	157.823	0.609	0.544
22	pm	33.963	33.381	0.234	0.816
23	am	44.027	41.620	0.710	0.480
	pm	24.823	23.726	0.719	0.475
24	am	80.066	86.842	-1.000	0.321
	pm	83.140	78.019	0.454	0.651
25	am	62.916	60.433	0.513	0.610
	pm	53.242	50.821	0.161	0.872
26	pm	58.585	49.830	2.471	0.016*
27	am	83.592	89.219	-0.917	0.363
	pm	74.817	72.482	0.405	0.687
28	am	58.380	53.539	0.179	0.859
	pm	120.689	130.383	-0.831	0.409
29	am	53.186	48.990	1.641	0.105
	pm	85.149	86.460	-0.227	0.821
30	am	55.762	53.706	0.370	0.713

Key *p<0.5 **p<0.01 ***p<0.001

The results show quite clearly that it is not possible using this type of analysis to differentiate between the EEG of the subjects when they are in a no-odour condition, from when they are in an odour condition. The four significant results are not representative and it remains a possibility that they are simply chance effects.

Discussion

These results were surprising and disappointing. They suggest that the variability in the individual EEG data, despite being collected in the most careful experimental conditions, militates against detecting gross changes in the EEG related to odour presentation. Also it does strongly suggest that a powerful data reduction technique should be employed to reduce the number of variables studied. It was expected that a within-subject design, combining odour files and comparing them to a close approximation of a "baseline", differences would be apparent. As the differences are not apparent then obviously the question is, why? One factor could be the similarity of the odours used for the above analysis. When considering the experimental situation in which the fine fragrances were presented first, to try and preserve the subjects' discrimination, it is possible to imagine that after the second, third, or fourth trial of a fragrance subjects no longer responded in the way they had to the first odour. This is not to say that they did not notice the odour but their olfactory centers may actively be inhibiting any response because of the lack of novelty or strong interest remaining in the odours. This may be a manifestation of a "dumping" response. Alternatively, this may be habituation, occuring to the repeated presentation of perceptually similar odours, and this point is discussed further in the discussion chapter.

It may be that an individual's response to each of the fragrances was in fact different and that by combining them any small changes were lost in the multitude. However, to find a statistical technique that could deal effectively with single intra-subject records of the length of those in the present study is extremely difficult and the most productive approach would be to change the experimental methodology to capture the fine grain changes. This is discussed further in the last chapter of the thesis.

Another key factor may be that all of the wavebands and electrodes were considered. If, as it now seems, the EEG response to odours is a subtle one, then it may well lie buried in the mass of data. However, the results of this analysis and the reliability study above do suggest that if there is an odour signal buried in the EEG noise then it is not obvious. It may well not be distinguishable from the ongoing EEG and furthermore may be restricted to few electrodes in one or more wavebands. So far in this thesis, far from being able to distinguish different odour types by their EEG signature, it has not been possible to demonstrate a difference between the odour and no-odour conditions.

The next stage of the analysis procedure was to rectify some of the above problems and to attempt to reduce the amount of data under consideration.

Principal Components Analysis

Principal component analysis (PCA) is well known as a method of data reduction, to reduce the number of variables to the ones accounting for most variance in the data. After successful completion of such a procedure it would be possible to employ more traditional methods of analysis, such as ANOVA to analyse the remaining variables. To maximize the possibility of discovering the important variables, the records chosen for analysis were very carefully vetted. Because the nature and scope of the variables have a crucial bearing on the results and their interpretation, this is a most important stage of the analysis. Principal component analysis looks for the linear combination of variables that would best account for most variance in the data as a whole.

A possible reason for the lack of success of the SVD analysis was the use of the fine fragrance records, so for the principal component analysis it was decided that different odour records would be used. Furthermore, the possible confounding effects of the high levels of inter- and intra-subject variability were controlled.

Data Files and Procedure

Because of the similarity of the fragrances, four odours used were from the 2nd group: Linalyl acetate, Traseolide, Iso-valeric acid, and Androstenone, see Appendix 2. These odours form a diverse group psychometrically. Iso-valeric acid is strongly unpleasant, and had the highest unpleasantness rating in the psychometric study whereas Traseolide and Linalyl acetate are fairly pleasant. Androstenone is the most interesting psychometrically as it splits into two distinct hedonic tones. Three fragrances were also chosen. Pink Quartz because it was rated in the psychometric report as the most pleasant odour, by both male and female subjects in contrst to IVA above which was the most unpleasant odour. Blue Diamond and Imperial Jade are good candidates for study because they have been identfied by Howells (1992) in a multi-dimensional scaling analysis, as being consistently separate from the main group of odours. In addition Blue Diamond and Traseolide have the highest and lowest familiarity ratings respectively, in the psychometric study. Furthermore, Imperial Jade had the lowest pleasantness rating for a perfume in contrast to Pink Quartz which has the highest. Thus, these eight odours are found to be interesting on a psychological and a psychometric level. (see also the psychometric report results for details: 131) It was anticipated that their diverse nature and distinct character would lend the best possible support for a principal component analysis.

Furthermore, the EEG data files selected for the analysis, except Androstenone (see below), were chosen by recourse to the reliability study. For each odour, only those EEG graphs that had been correctly classified as one where "something significant happened" by 75% or above of the observers, were chosen. Also, because many graphs were identified as containing a change but the place identified did not match the place of odour presentation, the data files chosen were narrowed down further. In effect, only those EEG records where 75 % of obervers had identified a change consistent with the place of odour presentation were chosen for this analysis. Thus, the variability has not been

artificially reduced by a normalising procedure but the level of variability in these records is low demonstrated by their high reliability rating.

For androstenone the situation was different because it had not been used in the reliability study. So only those EEG records that suffered from artifact contamination were discarded. This was seen as an advantage as it would provide an extra point of interest in the interpretation of the principal component results. The variability of the other odorants used has been reduced to a minimum, but androstenone could be expected to contain higher levels and so will demonstrate if this is a confounding variable for this analysis. Below, is the number of individual subject EEG records that were chosen for the analysis. The morning and afternoon data has been combined to increase the amount of data available in order to run the analysis.

Table 1.7.2 Number of individual subjects' EEG data combined for a principal components analysis, for each odour

Pink Quartz	13	Linalyl acetate	11
Blue Diamond	9	Iso-valeric acid	14
Imperial Jade	12	Traseolide	14
Androstenone Pleasant	14	Androstenone Unpleasant	31

The principal component analysis was of the correlations amongst the power measurements from the 28 electrodes. Each analysis explored the combined effects of between-subject and between-frames (within subject) variation and covariation. Separate analyses were carried out for each odour, in each waveband.

Thus, 40 principal component analyses were carried out in total (8 odours x 5 wavebands). The results were expected to identify, for each odour and for each waveband, a particular set of electrodes that explain most of the variance in the data.

Results

Below, are the sorted component loadings for the first principle component for each odour for alpha and theta, the only two wavebands that have been identified in the literature as having possible relevance to odour processing. The results for the remaining wavebands demonstrated a similar pattern and are shown in Appendix 5.

Table 1.7.3 First sorted principal component loadings in alpha and theta

Imperial Jade				Blue Diamond			
Electrode	**Alpha**	**Electrode**	**Theta**	**Electrode**	**Alpha**	**Electrode**	**Theta**
CZ	.933	PZ	.882	C4	.920	FTC2	.984
CP1	.924	CP2	.881	PO1	.915	TCP2	.958
PZ	.891	FTC1	.841	CZ	.909	FTC1	.956
CP2	.890	OZ	.835	T5	.905	C4	.949
O2	.882	T6	.832	P3	.904	CP2	.943
PO1	.879	C4	.832	C3	.900	O2	.938
FP1	.859	TCP1	.832	PZ	.891	F4	.937
O1	.858	PO1	.831	TCP2	.889	F8	.936
F4	.853	FZ	.820	F4	.885	C3	.928
TCP1	.853	FTC2	.818	CP2	.881	FP1	.927
T6	.844	T5	.813	TCP1	.878	CZ	.926
F8	.835	FP1	.795	O1	.873	T6	.926
FP2	.831	FP2	.794	CP1	.864	T3	.923
OZ	.827	T3	.787	O2	.864	PO1	.922
FZ	.827	CZ	.783	FZ	.858	PZ	.919
F7	.824	PO2	.760	FTC2	.847	FP2	.918
T5	.820	O2	.747	OZ	.836	PO2	.912
FTC1	.811	F7	.735	FTC1	.831	FZ	.893
P3	.809	F8	.710	F8	.826	P4	.884
C4	.805	C3	.703	T4	.813	O1	.879
C3	.794	P4	.698	P4	.812	T5	.871
P4	.790	T4	.695	T6	.806	F7	.867
T3	.781	O1	.652	PO2	.801	F3	.861
PO2	.724	TCP2	.635	T3	.788	OZ	.797
TCP2	.695	F4	.608	F3	.771	TCP1	.779
FTC2	.693	P3	.559	F7	.771	T4	.776
T4	.687	F3	.394	FP2	.771	P3	.607
F3	.566	CP1	.324	FP1	.754	CP1	.529

Pink Quartz				Traseolide			
Electrode	**Alpha**	**Electrode**	**Theta**	**Electrode**	**Alpha**	**Electrode**	**Theta**
CZ	.921	FTC1	.925	TCP1	.910	TCP2	.927
TCP1	.905	CZ	.890	C3	.906	O1	.912
C4	.885	TCP2	.873	C4	.896	T5	.910
CP1	.883	C4	.872	TCP2	.895	OZ	.906
TCP2	.883	F3	.871	FP2	.892	FP2	.904
F3	.836	C3	.840	CZ	.888	F7	.903
FP2	.805	PZ	.839	F4	.884	C4	.902
C3	.804	FP1	.837	T5	.884	C3	.898
T6	.802	TCP1	.821	FZ	.883	FTC2	.894
FTC1	.791	FTC2	.801	PO2	.873	T3	.890
F4	.783	FP2	.798	PZ	.871	P3	.884
T5	.771	OZ	.779	FP1	.866	F4	.884
FP1	.771	CP1	.769	T6	.865	CP2	.873
P3	.767	T3	.752	F8	.863	FP1	.873
P4	.760	FZ	.749	PO1	.861	FZ	.869
FZ	.750	P4	.738	OZ	.854	PZ	.868
F8	.747	F4	.719	FTC1	.853	PO1	.868
PZ	.736	F7	.715	O1	.852	T6	.859
FTC2	.708	T5	.714	F7	.827	FTC1	.852
OZ	.684	T6	.709	O2	.824	O2	.851
T3	.668	F8	.697	F3	.808	F8	.850
CP2	.599	P3	.679	CP1	.802	F3	.844
O1	.578	PO2	.529	T3	.802	PO2	.838
PO2	.555	CP2	.522	T4	.792	P4	.828
T4	.542	T4	.515	P4	.791	TCP1	.814
PO1	.519	PO1	.402	FTC2	.753	CZ	.803
O2	.509	O1	.318	P3	.697	T4	.800
F7	.477	O2	.467	CP2	.649	CP1	.562

Iso-Valeric Acid				Linalyl Acetate			
Electrode	**Alpha**	**Electrode**	**Theta**	**Electrode**	**Alpha**	**Electrode**	**Theta**
C3	.932	FTC1	.895	P3	.926	TCP2	.925
FTC2	.931	CZ	.884	TCP2	.916	FTC2	.908
CZ	.915	PZ	.880	C3	.903	C4	.899
FTC1	.913	C3	.870	PZ	.902	PZ	.897
PO1	.893	CP2	.860	PO1	.900	CP2	.895
PZ	.889	C4	.850	P4	.885	C3	.892
FZ	.889	PO1	.833	OZ	.867	O1	.888
F3	.879	F3	.828	CP1	.862	OZ	.883
TCP1	.879	P4	.825	FZ	.861	FTC1	.876
T3	.879	TCP2	.817	PO2	.859	CZ	.874
O1	.863	FP1	.804	T5	.858	PO1	.869
C4	.862	PO2	.790	TCP1	.850	P4	.868
FP1	.861	TCP1	.787	O2	.842	O2	.856
T5	.855	FP2	.774	C4	.837	PO2	.852
T6	.830	FZ	.771	O1	.836	F8	.848
F7	.820	T3	.876	CP2	.819	T3	.825
CP1	.817	F4	.701	FP1	.807	T6	.809
OZ	.798	O1	.695	FTC2	.806	T4	.802
PO2	.792	T5	.672	FP2	.795	FZ	.795
FP2	.787	F8	.629	CZ	.768	FP1	.785
F8	.786	T4	.621	T3	.742	FP2	.751
F4	.778	OZ	.599	F8	.742	T5	.751
TCP2	.775	T6	.591	T6	.717	F4	.737
O2	.732	F7	.590	F3	.583	TCP1	.727
P4	.727	O2	.541	T4	.567	F7	.556
T4	.686	FTC2	.534	F7	.563	P3	.551
P3	.605	P3	.475	F4	.557	F3	.536
CP2	.481	CP1	.451	FTC1	.464	CP1	.184

Androstenone "Pleasant"				Androstenone "Unpleasant"			
Electrode	**Alpha**	**Electrode**	**Theta**	**Electrode**	**Alpha**	**Electrode**	**Theta**
PO1	.939	P3	.890	PZ	.913	C4	.907
PO2	.930	O1	.871	CZ	.898	FTC2	.903
C4	.915	C3	.859	TCP1	.862	O2	.861
P3	.884	FTC1	.857	TCP2	.852	C3	.851
OZ	.881	T3	.851	FTC2	.836	PZ	.847
O1	.878	TCP2	.832	OZ	.827	CZ	.833
FZ	.868	OZ	.812	PO2	.826	TCP2	.825
T6	.865	O2	.811	PO1	.825	PO1	.805
T5	.862	CP2	.810	FZ	.823	F8	.801
TCP1	.860	FP1	.805	C3	.816	O1	.796
FP2	.854	FP2	.803	P3	.808	TCP1	.793
O2	.845	CZ	.794	T6	.804	OZ	.793
TCP2	.841	F7	.771	O1	.804	P3	.792
FTC2	.841	C4	.763	C4	.795	PO2	.789
FTC1	.839	F3	.758	F8	.787	T3	.779
CP1	.817	FZ	.752	T5	.787	P4	.745
C3	.816	PO1	.743	T3	.781	F3	.719
P4	.815	PZ	.736	FP2	.771	FP1	.716
CZ	.807	T6	.716	O2	.753	FP2	.711
F8	.795	CP1	.711	FP1	.752	CP2	.707
FP1	.794	F4	.702	P4	.737	T4	.704
F4	.762	T5	.679	T4	.724	F7	.691
T4	.761	TCP1	.673	CP1	.693	FTC1	.688
F7	.757	T4	.668	CP2	.689	F4	.660
CP2	.735	F8	.661	F4	.568	FZ	.578
PZ	.723	PO2	.608	FTC1	.566	T5	.559
F3	.643	P4	.607	F3	.522	T6	.427
T3	.630	FTC2	.569	F7	.506	CP1	.432

Interpretation

What these results show is that this analysis is unable to reduce the data to fewer variables than originally present. The first principal component shows a generalised

activity pattern, i.e., all electrodes responded together. There is no smaller grouping of electrodes that can account for most of the variance for any of the odours used, in any of the wavebands. The next stage in this type of analysis is to move on to a consideration of the other components. As can be seen from the table below however, most of the variance in the data has been accounted for by the first component and the remaining variance drops off sharply.

Table 1.7.4 Percentage of variance accounted for by the first and second and third principal components, by odour, in alpha and theta

Odour	1st	2nd	3rd	Waveband
Pink Quartz	55 %	18 %	6 %	Alpha
	54 %	12 %	9 %	Theta
Blue Diamond	72 %	5 %	3 %	Alpha
	78 %	5 %	3 %	Theta
Imperial Jade	67 %	8 %	6 %	Alpha
	56 %	8 %	4 %	Theta
Trascolide	71 %	7 %	5 %	Alpha
	74 %	4 %	3 %	Theta
Iso-valeric acid	68 %	10 %	6 %	Alpha
	54 %	9 %	6 %	Theta
Linalyl Acetate	64 %	11 %	7 %	Alpha
	64 %	7 %	5 %	Theta
Androst. Ples	33 %	15 %	6 %	Alpha
	58 %	5 %	5 %	Theta
Androst. Unples	59 %	9 %	6 %	Alpha
	56 %	10 %	7 %	Theta

A series of scree plots, see Appendix 5, where the eigenvalues have been plotted against the total number of factors extracted, indicates in graphical form the importance of the first principal component and the rapidly decreasing importance of the further components. Because of the difficulty of interpreting the factors identified as the most

significant by a principal components analysis, it was not thought advisable to even attempt to extract any meaning from a small second component.

Discussion

This result is in accordance with the findings of Kendal-Reed (1990) who found that all electrodes reacted to an odour with an increase in power. It may be, as was suggested in Chapter 2, that the interesting effects are occuring within a more restricted frequency, or across two or more frequencies. It may also be the case that the variance left unaccounted for in this analysis may be crucial in distinguishing between no-odour and odour conditions, or between odour samples. Perhaps there is too much variance in the data for the principal components analysis to function properly, or that the best combination of variables to account for the variance is non-linear. It may also be that the effect of the odour is extremely short-lived and is lost in the four odour frames studied in these analyses. However, if this is the case then it is not possible to use principal components or related analyses because using the first frame before and after the presentation of the odour, simply means too little data for such an analysis to be valid. The final data analysis procedure is detailed below.

Discriminant Analysis

Introduction

The final analysis of this thesis attempts to support studies by Van Toller et al (1992) and Kendal-Reed (1990). The first study located a group of electrodes in the parietal/occipital region that were identified by a multi-dimensional scaling analysis as important and able to discriminate between different odours, i.e., the authors reported that the differing power values of these electrodes in alpha, can differentiate between odours. Kendal-Reed (1990) used this same group of electrodes in his analysis and found some significant differences. If these electrodes can discriminate between the odour samples in this study then they will have been demonstrated in three different studies, all using different methods of statistical analysis.

Data Files and Procedure

The electrodes used to discriminate the odour records in this analysis (i.e., the dependant variables) were: CZ, PZ, C3, P3, TCP1, CP1, C4, P4, TCP2, and CP2. These were the electrodes identified in the previous studies mentioned above that distinguished between different odour samples. Because this analysis was a replication the only waveband considered, was alpha, as this was the only waveband studied by Van Toller et al (1992) when they used adult subjects. Kendal-Reed (1990) studied only delta in three month old babies, using the same group of electrodes. The odours examined in this analysis were: Pink Quartz, Imperial Jade, Blue Diamond, Traseolide, Linalyl acetate and Iso-valeric acid. These odours were chosen for the same reasons as for the previous analyses i.e., they have been identified in the psychometric results as being very distinctive on the three dimensions studied, see page 158 for a full discussion. Only those frames where an odour was present, i.e., frames 5-8 were used from each subject. The odour frames for all subjects were combined into a single file. The chosen electrodes in alpha only, were then used to discriminate the different odours. Thus, the power values of the chosen ten electrodes should discriminate between the different odours. The discriminant analysis tries to predict continuous variables from categorical data, and takes a co-variance matrix as input. The variance was pooled across time of day and frames but the variance for subjects was controlled for.

The results demonstrated that these electrodes were able to discriminate between the six odour samples. The multivariate significance tests were significant and a number of electrodes were identified as being important in the univariate results for each electrode. After this significant effect was demonstrated, the author chose ten further electrodes at random to double-check the finding. This was to make sure that the result was because of the identified electrodes. The results of this discriminant analysis were even more significant and several further electrodes were shown to be of importance. This demonstrated that there was more happening than was anticipated. A further discriminant analysis, using all 28 electrodes in alpha, was again highly significant. This was an

unusual finding. Most studies using topographic mapping of the EEG response to odours show very weak effects, and more often, results that merely approach significance.

A number of follow-up discriminant analyses were undertaken at this point to obtain a wider picture of the effects being demonstrated. The results showed that the 28 electrodes in each of the five wavebands could discriminate between the six odour samples, at a very high significance level. At this point it became clear that these results may be artifactual. In order to test this, a futher overall discriminant analysis was performed on the data. This time however, the data for the before odour conditions for each of the six odours were added to the data file. Variance for subject, time of day, and frame was controlled for, and the interaction between the different odours and the before and after condition was tested. The results showed that 20 out of 28 electrodes gave significant univariate results, and in addition, the multivariate tests were highly significant. However, there was no interaction between odour and the before/after conditions. See Appendix 5 for the results of this overall discriminant analysis.

Interpretation and discussion

It was now clear that the result obtained was caused by systematic artifactual effects. The task now was to attempt to determine the source of the artifact. The first possible cause related to the methodology used, but this was considered unlikely because of the systematic nature of the contamination that had occured. In the experimental design, all of the presentations of the odours were randomised. To suggest a methodological flaw was responsible would entail suggesting that before presenting a particular odour to a subject "something" happened and that this "something" happened each time that odour was presented to all of the subjects. Not only this, but it must have had a similar effect on each of their EEG records. The same scenario would now have to apply to each of the odours studied in this analysis. It is doubtful this could be achieved in practice even if it was the stated aim of the experiment.

Cuing seems unlikely to be responsible, because of the perceptual isolation that the subjects' were in. Even if it could have happened, the same problem as above occurs, that it would have to be a systematic effect, different for each odour, and producing the same effect on the subjects' EEG. Thus, a methodological flaw was considered extremely unlikely.

The obvious next source of contamination was the data itself. The data used to construct the data file used in the discriminant analysis, had been through several manipulations after being downloaded from the Brain Imager. It was possible that some systematic error had crept into: (a) a column in the data file; (b) the missing data distribution; (c) the power data itself. To check on the first of these possibilities the data file was thoroughly examined and it was confirmed that each column contained the correct figures. The second possibility was considered unlikely but was nevertheless checked (EEG artifact was deleted "blind" and covered all data files and all wavebands). Because the discriminant analysis programme deletes all values in a row if it contains a single missing data point, descriptive statistics were produced for all of the electrode data used in the analysis, for each odour, for each before and after condition. A study of this data revealed no obvious or systematic patterns that could account for the effect. Finally, the author took random samples of the data from the discriminant analysis file, including different subjects, odours, times of day, wavebands and electrodes. These values were all checked back to their original data files on the Brain Imager, before the data had been downloaded. All of the values were correct, so there is no doubt that the power data tested by the discriminant analysis, is the original power data, produced by the Brain Imager. No apparent errors seem to have occured in the downloading procedure or the subsequent file manipulations.

The programme used to run the analysis, i.e., SYSTAT has been checked by running through exercises, given in the accompanying text-books. No problems or errors have been discovered.

This leaves an extremely unsatisfactory and, at this time, unexplainable result. There is only one possibility that cannot be checked, namely that the Brain Imager itself produces data that is in some way systematically varied that has combined with this particular analysis, to produce this result.

Validation

The anticipated final stage of the analysis was unable to proceed because of the nature of the findings. No analysis was attempted on this data set for two main reasons. No grouping of electrodes, nor any feature of the data was identified in the first data set as being important in distinguishing between a no-odour record and an odour record, either within or between subjects. Neither has it been possible to demonstrate any reliable and replicable changes in topographical EEG data between different odours, either within or between subjects. Secondly, the final data set included only fine fragrances which had proved to be less useful than expected and were not considered, after the analysis of the first data set, to be sufficiently different from each other to justify a further analysis. After the lack of positive findings in the first analysis procedures, the only valid way to progress is seen to be a consideration of the entire experimental protocol and a re-evaluation of the assumptions underlying the thesis. These points are dealt with in the two final chapters of the thesis, which provide a discussion of the present study and give a suggested outline for future studies.

CHAPTER EIGHT

Discussion

This chapter and the next, aims to assess the contribution of this thesis to the field of the EEG response to odours and suggests improvements that could be made to the methodology in future work. The present chapter concentrates on a thorough examination of this study and considers the possible reasons for the lack of positive findings.

The experimental hypotheses stated in Chapter 4 were:

1). There will be a significant difference in the B.E.A.M odour response compared to the no-odour response, across/within subjects.

2). The topographic patterning will differ reliably with odour type, within/across subjects.

3). The topographic patterning will differ depending upon the psychometric response, across/within subjects.

It can be stated that not one of these hypotheses has found experimental support in this thesis. The reasons for this are many, and they are discussed below. However, this thesis also has a large exploratory and empirical component and the issues and assumptions of previous research considered here, together with the recent developments in non-linear analysis and brain theory, mean that the conclusions reached in this report will have far reaching consequences for future work in this area. One of the major problems of studying the EEG response to odours has been the lack of a thorough conceptual framework and the lack of vigorous discussion of underlying assumptions. Hopefully, this thesis goes some way to satisfying these requirements.

The present study is the largest of its kind ever undertaken. It is the first study to examine the impact of such a large number of odorants, with such a large subject group,

in a longitudinal design. It is also the first to consider thoroughly the complex issues surrounding EEG and the analysis of EEG data as they relate to the brain's processing of odours. The data analysis procedures reported in this thesis are the most comprehensive undertaken in this area, and the methodology used is the most advanced for this type of study. The issues discussed below will lead to a re-examination of the whole topic of the effect(s) of odours on the EEG and will question the assumptions presently held by researchers in this field.

There are several possible reasons why the data collected and analysed in the present study have failed to support either the experimental hypotheses or other work published on the same topic. The reasons can be considered under separate but related headings: the odours chosen for the study; limitations of the technology; the methodology; data analyses issues, and finally the possibility that there is nothing to find. This chapter considers the implications of these factors, not only for the present study but for future studies and the whole premise of using EEG to study odour processing in the brain.

It is possible to say with hindsight that the odours for the present study could have been better chosen. Because at the start of the study it was unknown how odours may affect the multiple lead EEG, many odours were considered and included. It was also not known how different odours had to be, to produce various topographical patterns. The fragrances were included largely for commercial reasons and partly because there was a great deal of consumer data for these fragrances (held by Quest International) that could be correlated with the physiological data. The fragrances were of very different types and were able to be discriminated easily. However, the task for the subjects in this experimental situation was not to discriminate the odours but just to smell them. It is entirely plausible that subjects became bored very early on in the presentation sequence of what to them seemed perceptually very similar odours. In effect, they habituated rapidly.

The fragrances were always presented first to preserve the subjects' discrimination, which was entirely the correct decision, as presenting them between the other odours would

have increased the tendency for this effect to occur. The inter-stimulus interval, which was at least two minutes and usually longer, was not sufficient for the subjects to "reset" their expectations of a fine fragrance (in fact they would only be able to reset their expectation when a very dissimilar odour was presented). This effect must have worsened in the afternoon session, when subjects began to realise that the same odours were being presented. Despite instructions to pay attention, one can imagine the tendency of subjects not to concentrate, especially with seemingly similar odours.

One further point to be considered is that the fragrances are very complex mixtures. Of course, most of the smells that people detect on an everyday basis are mixtures, but for experimental purposes it may make more sense to use either pure, simple odorants or some simple mixtures that have ecological validity.

The four additional odours used in the experiment were chosen for their very diverse character. The fact that they too failed to show positive findings may be because of the technology used, the data analysis, or the possibility there may be no effect that an odour has on EEG.

The solution? Future work should not include so many perceptually similar odours; three would seem to be reaching a maximum after which subjects will start to habituate and lose concentration. Also, the odours should be as chemically simple as possible. Perhaps even a single fragrance should be included in an experimental group because a related question concerns the number of odorants used in an experiment of this nature. Because the effect(s) of the odours on the topographic EEG are unknown, the temptation in an exploratory study of this type is to include many candidates that may produce interesting effects. The time, complexity and expense of running such an experiment also combines to make the testing as comprehensive as possible. With hindsight, the second group of odours chosen were more likely to lead to interesting results. They were all perceptually very different, at least one was distinctly unpleasant to the majority of subjects, and there were only four in the group. The fact that no significant results were

achieved using these odours was a surprise and the reasons for this are considered to lie somewhere other than with their identity.

The blank records in this study were not thoroughly analysed for the following reasons: the reliability study indicated that blank EEG graphs were not distinguishable from the odour graphs, either between or within groups. To look at the within subject differences in the SVD analysis, a "baseline" state was constructed from the no-odour frames of odour trials, there was not enough data in a subject's blank record. Blank records were not included in the PCA analysis because it was used to reduce the dimensionality of the data, not as an analysis procedure per se. It was the original intention to use the identified electrodes from the PCA to examine the data further. When the results were unable to identify significant electrodes the next step was considered to be a replication of past studies (Kendal-Reed 1990; Van Toller, 1991; and Howells 1992). These studies identified significant electrodes that distinguished odour samples. Blank records were anticipated to be added to the discriminant analysis procedure, as were the records for androstenone, but the serious artifactual effects that occured precluded this.

A further question relates to the contribution that the blank records may have made to the results. Several points became clear during the research period that suggest that blank records may not be as useful as previously thought. Lorig (1989) has suggested that blank records are not true controls because of subjects' expectation of an odour that may alter the EEG. Although, in this study this possibility was controlled for by instructing the subjects' not to expect an odour each time, this remains a possible confounding effect. According to this view to combine all subjects' blank records into a single file would be misleading when compared to grouped odour records. To combine all the blank records would be misleading because of the high level of individual variability present in EEG data. The assumption when combining the odour files is that the EEG will be affected by the odour, hopefully in a key few electrodes in a certain direction (increasing or decreasing power), perhaps in certain wavebands. The same cannot be assumed for the

blank records. To overcome the problem suggested by Lorig, an EEG could be recorded for a sufficiently long period to be able to use this as a "blank" record.

Another possible reason for the lack of positive findings may be the equipment used. The B.E.A.M system used is relatively old, although its major drawback is the amount of pre-processing that it carries out automatically, in particular, the problem of obtaining the raw data. This was not possible for this study with the FFT being carried out on a dedicated chip in the machine. This means that the signal available for analysis is automatically split into five frequency bins. The raw EEG data would have been more amenable to different types of analyses, particularly autoregression techniques. The application of non-linear methods to the data such as Chaos analyses would also be possible and this is discussed in the final chapter. A later point also covered in the final chapter is the potential with improved technology to examine a much narrower range of frequencies. Basar (1989) has suggested that a small range of frequencies are important for the transfer of information within the brain. In addition, the more recent brain mapping systems, automatically produce the raw data and can manipulate it in various ways, avoiding the necessity to utilize complex downloading procedures which may increase the risk of error. A further question mark has also been raised over the use of this technology because of the results obtained in the discriminant analysis that may have been caused by the internal processes of the Brain Imager. The question of the equipment used is inextricably linked to the issues of potential data analysis techniques, many of them considered in Chapter 4. After a consideration of the methodology used in this study, the data analysis procedures used in the present study will be examined.

The methodology used in this study only requires minimal changes. The subjects are in a restricted perceptual environment, which maximises the potential of the odour signal to be detected. Criticisms that could be levelled at the methodology concern the moment of presentation of the odour and the length of the recording session. In the first main experimental testing session, the odour was presented at frame 5 and at times this did not coincide with the inhalation cycle of the subject. This is the reason for the use of four

frames of odour data in the analysis procedures, as it was assumed that the response would definitely have appeared within this time frame. It is not at all clear that the response could be located in that first frame after presentation and so all of the odour frames were examined. This is one possible weakness of the study by Howells (1992) in that the first frame only after presentation was examined, and for some of the data used the subjects' had not inhaled and were at various stages of exhalation. This implies that some of the demonstrated effects may be artifactual and not a consequence of the odour presentation.

It is obviously important that the point of inhalation is determined as closely as possible, however when this study was begun, it was not known whether or not the presentation of an odour would produce a reasonable signal in the noise of the EEG. This study used the most up to date methodology including the low odour room, which was expected to produce the best chance for obtaining EEG data with a lower level of variability. The second experimental study was modified to include a respiratory transducer which subjects wore around their chests, but unfortunately the equipment failed to function properly on a regular basis, so it is unknown whether the data collected after the point of breathing would have provided different findings.

It is also the case that presentation at the point of inhalation is only an approximate method for ensuring the arrival of a sufficient amount of odour at the olfactory epithelium at a particular time, which is presumed to be a precursor to a rapid brain response. However, with the equipment used it seems quite feasible that the response is so rapid it is lost within the 2.56 second averaging procedure. This is considered later on in this thesis. The only way to be more precise is to use an olfactometer, but this means that the naturalistic sniffing process is lost. However, as an olfactometer also gives precise control of other factors such as air flow and concentration the advantages appear to outnumber the disadvantages, but only further experiments will resolve these issues.

A further question related to the methodology is the length of time over which the EEG is recorded. This question relates also to the equipment used in this study and data analysis

procedures. EEG data in this study was recorded for a total of fifteen frames, which is just under 40 seconds, during which the odour was presented for just over 10 seconds. The length of time the odour is presented for is not under discussion, it is quite clear that the EEG response will occur within this time, the question here is how much data is recorded prior to the point of presentation. This is where the issues of data analysis techniques become crucial. The studies by Van Toller et al (1992) only analysed data from the first frame after presentation. Kendal-Reed (1990) studied the frame before and the frame after presentaton. It seems more reasonable to try and characterise the EEG fully, before considering the impact of an odour. The EEG is highly variable and so the danger of combining random fluctuation with odour related effects is very real if only one or two frames of data are examined.

Considering the results of this study, it is obviously more difficult to demonstrate the effect(s) of an odour on the EEG when analysing more than two frames. However, in order to fully characterise the EEG, the data for even this study may not be sufficient. Gevins (1987), suggests that at least three minutes of EEG data are required to be able to achieve sufficient characterisation. This is where questions of the technology and data analysis come into play. Assuming that the brain response to odours is very rapid and may be present at specific frequencies (Basar, 1988), then raw EEG data must be collected and digitised because only the raw data will contain all of the necessary detail. Using B.E.A.M. with its built in FFT, it is possible to capture all the significant changes taking place in an EEG record which may be sufficient for clinical use, but for an exploratory analysis more detail is required. The problem with this route is the difficulty of analysing such data sets. Many of the problems have been discussed in Chapter 4, but the problem still remains of how to descriptively or statistically characterise large EEG data sets.

Here again, it is a great advantage if the data has not automatically been through a clinical Brain Imaging system, because then it is possible to obtain a long time series of sufficiently short epochs that are ameanable to autoregression analyses. Such approaches

are probably the best way of characterising long EEG segments. This then raises the question of whether this technique can be used on the relatively short periods of EEG data necessary to capture a possible EEG response to an odour.

If it is the case that there is a rapid brain response to odours, then it is going to be extremely difficult to catch. Only if such a response was consistent; within subjects for certain odours; or within subjects for all odours; or across subjects for certain odours; or across subjects for all odours, will it indicate that this response is related to the presentation of an odour. Thus, the response may be: different for each subject; a general "odour response"; or different odours may produce different effects in the same subject. Alternatively, the majority of subjects may respond to all odours in a particular way, or different odours may produce different responses that are nevertheless consistent across subjects. This problem highlights an earlier point in this thesis, namely, that by comparing only the output of "systems" it is not possible to progress very far, if you are not considering well defined clinical populations. This is a significant problem for the field of the topographical mapping of the brain's response to odours. This is where the recent developments in non-linear analyses offer the field an attractive, alternative approach.

It may be possible to study the EEG response to odour by using an ambient odour paradigm. This may prove to be the most productive approach, especially when linked with the new chaotic methods of analysis. It may be possible with a sufficiently long time series, taken both in and out of an ambient odour environment to determine if the odour changes the dimension of the EEG.

Concerning the data analysis in this study it is clear that in one way there was too much data and in another way there was too little. There was too much because too many variables were chosen for analysis, this made the technical, practical and theoretical aspects of the study problematic. The ratio of variables to subjects was extremely unfavourable when considering statistical analyses. There was too little in that the EEG data was not recorded for long enough to be able to fully characterise it, before the odour

was presented, i.e., the time series was too short and this precluded many analysis procedures. In effect, EEG studies have to negotiate a trade-off between the practical problems of testing large numbers of subjects, resulting in the inevitable data handling problems, and the validity of a study that has rather less data but too few subjects.

There has been the ever present difficulty in this study because of its exploratory nature, of using considerable amounts of intuition, particularly in the data analysis. One of the problems has been the usefulness of group data compared to individuals' data. It is quite possible in EEG work to be able to identify different groups in a data set on the basis of certain features, but then discover that no one individual in any of the groups displays such features. This happens because the separation of groups depends upon the difference in mean values whereas the ability to "diagnose" individuals depends upon the distribution of individuals in each group, and particularly on the population overlap. Thus, the results of the present study were expected to provide basic information about the EEG differences rather than to provide useful "diagnostic" criteria.

One further reason for the lack of positive results is that too much was attempted. This study by necessity adopted almost a scattergun approach to the problem of the EEG response to odours using what knowledge was available to guide the intuitive process. The problem of the EEG response to odours is extremely complex and the considerations and findings of this report will allow future researchers to be more focused and less ambitious in their aims.

The final question in this section is probably the most important. Based on all of the information contained in this thesis, is it likely that there is an EEG signal that is related to odour presentation and one that can be detected using current EEG techniques ? Did this thesis fail to find any positive results because in fact there is no detectable or decipherable odour signal present at scalp level ? Based on the work contained in this thesis, one conclusion may be that it is not possible to detect a reliable EEG response related to the perception of an odour. However, we may qualify this statement and say that using B.E.A.M in this experimental paradigm it has not been possible to isolate such

a response. By using a different experimental paradigm, with different equipment it seems entirely likely that such odour effects on the EEG will be found:

"I think that if you select the right type of experimental paradigm and recording, you can learn a lot about how the brain works. You can also be misled however, unless you choose the stimulus and your hypothesis very carefully." (Grusser, 1989: 486)

The evidence for such a statement is based on two things: the fact that odours (some more than others) represent important pieces of information for the CNS to process, which entails the transfer of this information from one stage to another; and secondly that the EEG is a reflection of such information transfer processes. The question then becomes, based on all the thorough considerations in the present thesis, how may the effect of odours on the EEG be demonstrated? The final chapter of this thesis suggests some possibilities.

CHAPTER NINE

Conclusions & Future Directions

The main conclusions of this thesis are listed below:

(1) It has not been possible in the present study using the present methodological paradigm and topographical mapping to demonstrate the effects of odour on the EEG.

(2) Because certain odours can be conceptualised as important pieces of information for the organism, and as the EEG can be conceptualised as a process whereby the brain transfers information from one part to another, then we may expect that the effects of odour could be reflected in the EEG.

(3) Because of the advances made by conceptualising the olfactory system as a computational system, and by the incorporation of Chaos theory into neural network models of the olfactory system, it is now possible to develop alternative and physiologically valid theories of the processes that occur in the olfactory system.

(4) Because of the recent development of Chaotic, non-linear methods of analysis, it is now possible to go beyond a phenomenological approach to EEG data.

(5) Taking all of the above into account, with the correct experimental paradigm(s) these new approaches to the study of olfaction hold the promise that it may be possible to demonstrate the effect of odour on the human EEG.

The conclusions above, that have developed out of this thesis, have led to the formation of three possible ways ahead for research of this type. There is not sufficient evidence at present to suggest that any one of these approaches will be more fruitful than the others, but they all offer theoretically based, viable and practical ways to study odour perception using the EEG. Possible unresolved problems that may hinder progress will be identified in the following discussion.

This thesis has illustrated the problems both theoretical and practical in the analysis and interpretation of EEG data. Standard statistical procedures are not sufficient when dealing with data sets of such complexity. For work of an exploratory nature traditional statistics fail to perform well. It is clear that unsolved questions regarding the postulated functional significance of the EEG in relation to odour perception handicap many studies of this type. It is unclear what questions to ask and how to best analyse any collected data. However, the new methods for analysing EEG data that have developed out of the recent developments in Chaos theory may provide a useful alternative approach. Such non-linear interpretations of time series data offer not only new analysis techmiques but also the possibility of designing testable models of the EEG process and related experimental manipulations. Conceptualising the brain as a dynamical system that demonstrates chaotic behaviour also means that it is possible to design experiments with specific hypotheses in mind, as detailed further on in this chapter.

In his global review of the quantitative analysis of the EEG, Jansen (1991) details the traditional methods most often chosen to analyse EEG data and reports on the possibilities opened up by recent non-linear approaches. He maintains that the previous twenty years of EEG analysis have proceeded on the assumption that the EEG is produced by a very complex system. Up to now researchers have progressed by comparing the output from subjects from two different states, either physiological or experimental, or from two different clinical populations. Using the new mathematical approaches would remove this limitation.

Characterising the EEG signal as the output of a deterministic system however, leads to new methods of analysis. As we have seen in Chapter 3, any dynamical system that has at least three degrees of freedom can exhibit chaotic behaviour. Jansen (1991) defines Chaos thus:

"The easiest way to define chaos is by stating what it is not, namely, bounded steady state behavior that is not an equilibrium point, not periodic and not quasi-periodic. A chaotic system produces output that varies unpredictably, and in that sense resembles random

noise, but the current output depends in a deterministic, rigid manner on the previous output, which distinguishes it from random noise." (Jansen, 1991: 107)

The main concepts in Chaos theory are those of: phase space, trajectories, attractors, basins of attraction and sensitivity to initial conditions. The first step in any dynamic analysis is the construction of a phase space / portrait, which requires only a single time series. This translates to a single EEG lead. A single time series is all that is required because present output depends entirely on previous output, so all the relevant variables can be constructed from this single time series using the "lagging method" (Babloyantz, 1989). This method displaces the original time series by successive increments and so creates multiple readings which means that the space spanned by the variables will be topologically equivalent to the original phase space and represents many of its dynamic properties (Babloyantz, 1989). Multiple recording sites can also be used in a method developed by Eckman & Ruelle (1985 cited in Babloyantz, 1989) or a method based on singular value decomposition, developed by Broomhead & King (1986). By plotting these points in a phase space, the trajectory of the system can be examined and the type of the attractor can be determined, the three main types being: a point attractor, a limit cycle attractor (either attracting or repelling) or a strange attractor.

Thus, it is possible to reinterpret time series as multidimensional geometrical objects and in doing so move beyond the information gained from the more classical approaches based on autocorrelation and power spectra as detailed in Chapter 3. These are based on an EEG signal that has been decomposed by a Fourier Transformation and so implicitly carry the assumption of the presence of periodic oscillation in the signal. The chaotic approach to brain function proceeds on the assumption that the EEG signal is produced by a deterministic dynamical system and not by the superposition of a number of periodic oscillators (Mayer-Kress & Holzfuss, 1985).

Dynamic systems can have more than one attractor but each one is characterised by a set of initial conditions that results in a set of trajectories to that attractor. A slight change in initial conditions for two trajectories and they soon start to diverge because of the

stretching and folding that takes place in the phase space. Despite this, because the behaviour is bounded, both trajectories will occupy the same state space in the case of the limit cycle, and the same attractor in the case of a strange attractor although these trajectories never intersect.

A different way to view attractors is by plotting their Poincare map, or first return map. Anything you see in a mapping of n-dimensional space can also be seen in a flow (n+1) dimensional space. Conversely, to understand flows in (n+1) dimensional space, you can look at mappings in n-dimensional space, which has the effect of slicing through the attractor. The trajectory of the attractor will pass repeatedly through this plane and by marking the points where it does, the silhouette of the attractor is revealed.

The method of characterising the attractor is by determining its dimension, this distinguishes deterministic from random behaviour. The dimension of an attractor is a measure of the independent variables needed to specify its state at a given time, and can be considered a measure of complexity (Mayer-Kress & Holzfuss, 1985).

"The dimension of an object is the smallest dimension of the space that can accommodate this object without producing zero volume. In case of a planar object, the dimension would be 2, because a plane does not fit in a one-dimensional space, and it has zero volume in a three dimensional space. Similarly, a line is a one dimensional object and a point a zero dimensional object." (Jansen, 1991: 109)

Strange attractors are characterised by their fractal dimension, which indicates self similarity over a range of scales. Two orbits on a chaotic attractor cannot diverge exponentially forever, so the attractor folds over onto itself, a process that occurs repeatedly creating the fractal structure that can be revealed over different scales (Stewart, 1989).

It is important to realise here that the application of Chaos theory to the analysis of EEG signals is at the very early stages and although the results achieved so far look extremely promising, caution is necessary when turning to interpretation:

"First, one should realise that many of the techniques used to study chaotic dynamic systems were originally developed for situations where the (non-linear) differential equations that governed these systems were available. Although the embedding theorem by Takens makes it possible to apply the same techniques to an observed time series, one should be aware that the results so obtained are only an approximation, which is especially true for the attractor dimension estimates." (Jansen, 1991: 111)

The correlation dimension was the first dynamical tool pressed into service in the search for Chaos in the human EEG. By plotting trajectories in the phase space the correlation dimension D_2 can be determined:

"An often used method is based on the so-called correlation dimension D_2 for which an efficient algorithm has been developed. The algorithm proceeds from the assumption that one has collected N points of a trajectory on a strange attractor embedded in a m-dimensional space." (Jansen, 1991: 111)

Several researchers have shown that the correlation dimension alters with different physiological, pathological, and task states, including sleep stages, Creutzfelt-Jakob disease, Alzheimers disease, and epilepsy (Babloyantz, Nicolis & Salazar, 1985; Babloyantz & Destexhe 1985; Mayer-Kress & Holzfuss, 1985; Roshke & Basar, 1988; Soong & Stuart, 1989; Pritchard & Duke, 1991; Pritchard, Duke & Coburn, 1991). The conclusion would seem to be at this stage that the correlation dimension increases with the level of activity, which implies that the level of Chaos rises. However it is not clear exactly what this means. The inherent problems in estimating the correlation dimension are several levels: the choice of the time lag, the data length and the sampling frequency suggest that only a broad indication of state is provided by this measure. Nor is it clear what "more Chaos" in a dynamical system means:

"Is an EEG that goes from dimension 5 in stage two sleep to dimension 6 with eyes closed, to dimension 9.5 with eyes open becoming more complex ? The correlation

dimension is not a measure of complexity of causes, in a common sense meaning, as distinct from elaborateness of consequences." (Bullock, 1989: 545)

Already it is clear that the use of the correlation dimension may be treated in a phenomenological way by some researchers as the "magic single feature" (Jansen, 1991: 114) which should be discouraged. Many researchers have emphasized the better use of Chaos analysis in developing and testing realistic models of EEG generation, and the success of Freeman (1987, 1989) in developing such a model should encourage more careful work in the same vein.

The determination of the correlation dimension is often not based on ideal conditions. Pritchard & Duke (1991) specify what the ideal conditions are: (1) an unlimited amount of noise-free data is available, (2) the dynamical system governing the time series remains stationary, and (3) the dimension of the embedding is sufficiently larger than the actual fractal dimension of the reconstructed attractor, then this estimate is equal to D_2 the correlation dimension (Pritchard & Duke, 1991: 3). As the authors point out these conditions are not met with experimental EEG data. Further problems that must be considered when applying the application of the correlation dimension to EEG data have been fully discussed by Theiler (1990) and Albano, Mees, de Guzman & Rapp (1987).

Moreover, the studies above are mostly based on the single lead approach, but this has practical and theoretical implications. It is theoretically justifiable if the EEG is deterministic and globally coherent and the data obtained from embedding the single time series provided the dynamics of the whole system (Mayer-Kress, Barczys & Freeman, 1991):

"However, in typical cases the coherence of the EEG is only partial, as evidenced by the differences among reconstructed attractors obtained from different leads. If in studies of specific sensory and motor events one is interested in the stimulus- or response-dependent dynamics of only a limited area of the brain, single EEG traces suffice; but in general one is interested in a larger neural region and thus, one has to take into account

spatial as well as temporal aspects of EEG dynamics." (Mayer-Kress, Barczys & Freeman, 1991: 2)

The authors suggest that there are three approaches to the "Chaotic" analysis of multi-lead EEG data. In the first the brain is seen to function as an organic whole and that the time series derive from a global attractor of a finite dimension.

"The signal from each lead is inferred to have local components and a global component associated with the deterministic brain attractor. Each of these components contributes significantly to the signal at each electrode, thereby contributing a large noise component (from the "non-enslaved" neurons) as well as large redundancy from the global, coherent component which is picked up at a number of electrodes simultaneously. However [this approach] offers no insights into the underlying neural processes." (Mayer-Kress, Barczys & Freeman, 1991: 2)

The other extreme is apparent, i.e., to assume that a single attractor contributes to each lead but this approach is also limited. The third approach is to decompose the EEG into orthogonal modes to examine the structure of the spatio-temporal signal as it unfolds over time over the chosen area of cortex.

Obviously the number of data points required to characterise an attractor depends upon the structure of the attractor, the distribution of points on the attractor and the precision of the data (Albano et al, 1987). The methods presently available are not sophisticated enough to utilise such a relatively short time series that exists in the data collected for the present set of experiments. Furthermore the technology used for the present study determines the length of the data segment and an important factor in estimating a reliable correlation dimension is flexibility in the length of the EEG segment. Despite the fact that it has not been possible at present to utilise the above non-linear methods of chaotic analyses in this study, it is important to be aware of these very recent approaches in the field of EEG analysis. In particular, attempts must be made to integrate the two

approaches now available. The results of a traditional approach to the data should be considered in the light of the non-linear "chaotic" models of brain function.

The fundamental problems facing researchers trying to decode odour related information in the EEG are that only a subset of the brain may be processing this information, whilst simultaneously many other brain areas will be active. There is no reason, at present, to expect this odour related processing to occur in a particular anatomical location, which may be the case in visual or auditory processing. Furthermore, the processing of olfactory information is probably widely distributed and constantly shifting. Therefore, the task is to identify some constant in the noise. Even if this thesis had been successful in identifying significant electrodes that discriminated, either between a no-odour and an odour record, or between different odour records, problems of interpretation remain. Significant results in the literature often suffer from interpretation problems. These include: effects in alpha and theta being distinguishable from the possible effects of arousal; the problems of distinguishing a sensory from a cognitive event; and being restricted to noting a change in topographical distribution without any possibility of relating this to underlying structures. One conclusion has to be that some of the effects demonstrated have no intrinsic existence outside a particular experimental paradigm. Thus, it is hoped that the improvements in analysis suggested above and improvements in methodology suggested below, will begin to overcome some of these problems.

An extremely important question that has to be addressed is the technology to be used in future studies, as this has an enormous impact on the questions that can be effectively answered. To some extent, in studies of the effect of odours of the EEG, topographical mapping is misleading. The topographical maps produced are useful for visualising EEG events but can lead to many problems of misinterpretation. Because users of topographical mapping systems need to have only minimal experience with the conventional EEG, there is a risk that these systems will be used uncritically. The problems associated with the coloured maps are many. The maps do not contain any more information than a conventional EEG trace, and do not in themselves constitute a

form of data analysis. Furthermore, visual selection of maps for analysis introduces a considerable amount of subjective bias. However, if the experimenter is aware of such problems and relies more on the data produced than the visual display, these problems can be overcome.

What the brain imaging technology does offer is a way of obtaining the information generated by the cortex present in scalp potentials. Only the EEG (and possibly the magnetoencephalogram, MEG) provide the necessary spatial and temporal resolution to be able to read the spatio-temporal messages generated by cortical neural activity in response to an odour. Problems abound, however, when trying to read these messages, as the results of this thesis have demonstrated. The basic requirement for interpreting these signals is to determine the before- and after-patterns of neural activity.

Recent developments by Freeman (1989) tell us where and how to look for such information. It appears however, that improvements in present technology must occur first. Freeman maintains that the information contained in the EEG is carried by a common oscillatory waveform in brief wave packets of about 100ms. These "carrier waves" of information appear to operate at frequencies of 15-20 Hz, although Freeman suggests that the optimum frequency is 40-50 Hz,with significant information in the 80 Hz and above range. These frequencies are compatible with the notion of information being carried in spatial form. An amplitude pattern can be specified in 100ms (4 cycles at 40Hz), but this is not time enough for a phase pattern (i.e., temporal) to be established.

To extract such information from the EEG would require digitisation, occurring at rates of 500 samples/second/channel, in order to examine the high frequency ranges (Freeman, 1989). This is not yet possible with commercially available systems, but steps can be made in this direction. Freeman has generated his theories using the paleocortex of rabbits, but it seems plausible to suggest that the same principles of mass neural activity could be generalised to the human neocortex.

There is as yet no demonstrated neocortical representation for the olfactory system. This means that the electrodes, in order to demonstrate the expected diffuse spatio-temporal effects, have to be distributed over as much of the cortex as possible. Because it is still not clear that any location(s) will be found, then it is advisable to use more electrodes than in the present study. Gevins (1987) uses up to 64 electrodes and suggests that even more - up to 256 - could be used in future studies.

Several authors have suggested that some specific EEG frequencies have a role in information processing in the brain. (Basar, 1989; Sheer, 1989; Freeman, 1991; Ketchum & Haberly, 1991) The role of such frequencies is not yet determined but it seems reasonable for future studies to be aware of these postulated functional frequencies and to design experiments accordingly.

Suggested improvements for future studies of odour processing are given below. In general, future work may benefit from attempting less, in terms of the numbers of subjects and odorants used. If possible, the number of electrodes used should be increased, and studies must have the ability to analyse the data before it is run through a spectral analysis facility, such as the FFT. Studies may be improved by collecting the EEG data for long enough periods for it to be sufficiently characterised, but must ensure that the data is amenable to the analysis procedures able to do this. Ensuring that raw data is available will make it possible to examine the specific frequency ranges, for example, 10Hz.

It may be possible to use a repeated presentation paradigm, in that one odour is repeatedly presented to a subject. Several authors have suggested (Basar, 1989; Freeman, 1991) the expectation of a particular event, in this case the identity of an odorant, produces a replicable EEG pattern and such a paradigm may discover if this is the case. In effect, one would be searching for Freeman's "odour template" or Shepherd's "odour image."

Alternatively, an ambient odour paradigm may offer an alternative approach to the problem of odour related EEG changes. Two possible routes suggest themselves. The

first is to examine the possibility that pre-stimulus EEG affects an ERP. This could be examined in an odour vs a clean air, ambient atmosphere. The second possibility is a study of the dimension of the EEG recorded in an odour versus a clean air, ambient atmosphere. This could be examined with both "relaxing" and "refreshing" odours. An important feature of such a study would be the necessity to collect long time series of EEG data in order to make it viable for a non-linear analysis.

The development of new experimental techniques in mathematics has led to a renaissance in brain theory in which the brain is seen as a dynamic system subject to the laws of physics and chemistry that hold for other complex self-organising systems of the natural world. These analytic approaches place heavy requirements on the observation and measurement of the behaviourally related information content of the brain as the basis for assessing its dynamic operations.....This technology is now widely available, but it must be modified and extended to take full advantage of the wealth of information in the scalp EEG that brain theory predicts must be available for our clinical use." (Freeman & Maurer, 1989: 125)

References

Abt, K. (1983). Significance testing of many variables. **Neuropsychobiology, 9**: 47-51

Ache, B.W. (1991). Phylogeny of smell and taste. In: Getchell, T.V., Doty, R.L., Bartoshuk, L.M., & Snow Jr, J.B. (eds) **Smell and taste in health and disease.** Raven Press, New York. 3-19

Adey, R.W. (1972). Organisation of brain tissue: Is the brain a noisy processor ? **Int. Journal of Neuroscience, 3**: 271-284

Adey, W.R. (1988). Do EEG-like processes influence brain function at a physiologial level ? In: Basar, E. (1988) **Dynamics of Sensory and Cognitive Processing by the brain**. Springer-Verlag. Berlin. 362-368

Ahern, G.L., & Schwartz, G.E. (1985). Differential lateralisation for positive and negative emotion in the human brain: EEG Spectral Analysis. **Neuropsychologia, 23, 6:** 745-755.

Ahlstrom, R., Berglund, B., Berglund, B., Engen, T., & Lindvall, T. (1987). A comparison of odor perception in smokers, non-smokers and passive smokers. **American Journal of Otolaryngology, 8:** 1-6

Albano, A.M., Mees, A.I., de Guzman, G.C., & Rapp, P.E. (1987). Data requirements for reliable estimation of the correlation dimension. In: Degn, H., & Holden, A.V. **Chaos in Biological Systems**. Plenum Press. New York. 207-220

Allison, T. & Goff, W.R. (1967). Human cerebral evoked responses to odorous stimuli. **EEG & Clinical Neurophysiology, 23:** 558-560.

Amit, D.J. (1989). **Modeling brain function: The world of attractor neural networks**. Cambridge University Press. Cambridge.

Andreassi, J.L. (1980) **Psychophysiology: Human behaviour and physiological response**. Hillsdale New Jersey: Lawrence Erlbaum Associates.

Astic, L., & Saucier, D. (1986). Anatomical mapping of the neuroepithilial projections of the olfactory bulb in the rat. **Brain Research Bulletin, 424**: 144-152

Babloyantz, A. (1985). Evidence of chaotic dynamics of brain activity during the sleep cycle. In: Meyer-Kress, G. (ed). **Dimensions and entropies in chaotic systems.** Springer Verlag. Berlin. 241-245

Babloyantz, A. (1988) Chaotic dynamics in brain activity. In: Basar, E. (ed) **Dynamics of Sensory and Cognitive Processing by the brain.** Springer-Verlag. Berlin. 196-203

Babloyantz, A. (1989). Estimation of correlation dimension from single and multi-channel recordings: A critical view. In: Basar, E., & Bullock, T.H. (1989). **Brain Dynamics: Progress and Perspectives.** Springer Verlag, Berlin. 122-130

Babloyantz, A., & Callez, D. (1991). Probing brain dynamics. In: Dvorak, I. & Holden, A.V. **Mathematical Approaches to Brain Functioning and Diagnostics**. Manchester University Press. Manchester. 77-93

Babloyantz, A., & Destexhe, A. (1985). Strange Attractors in the Human Cortex. In: Meyer-Kress, G. (ed). **Dimensions and entropies in chaotic systems.** Springer Verlag, Berlin

Babloyantz, A., Nocolis,C., Salazar, M. (1985). Evidence of chaotic dynamics during the sleep cycle. **Phys Lett 111A**: 152

Basar, E. (1985a) EEG - Dynamics and evoked potentials in sensory and cognitive processing by the brain. In Basar, E. (ed) **Dynamics of Sensory and Cognitive Processing by the brain**. Springer-Verlag. Berlin

Basar, E. (1985b). Thoughts on brain's internal codes. In: Basar, E. (ed) **Dynamics of Sensory and Cognitive Processing by the brain**. Springer-Verlag. Berlin. 381-385

Basar, E. (1988). Brain waves, chaos, learning and memory. In: Basar, E. (1988) **Dynamics of Sensory and Cognitive Processing by the brain**. Springer-Verlag. Berlin. 395-406

Basar, E., & Bullock, T.H. (1989). **Brain Dynamics: Progress and Perspectives.** Springer Verlag, Berlin.

Basar, E., Basar-Eroglu, C., Roschke, J., & Schutt, A. (1989). The EEG is a quasi-deterministic signal anticipating sensory-cognitive tasks. In: Basar, E., & Bullock, T.H. (1989). **Brain Dynamics: Progress and Perspectives.** Springer Verlag, Berlin.

Boeck, J. (1980). Neural Basis of Coding of Chemosensory Quality at the Receptor Level. In: van der Starre, H.(ed) **Olfaction and Taste VII**. IRL Press, London.

Braitenberg, V. (1990). Reading the structure of brains. **Network, 1,** 1-11.

Brandle, U., Kobal, G., & Plattig, H.K. (1980). EEG - Correlates of olfactory annoyance in man. In: van der Starre, H. (ed). **Olfaction and Taste VII**. IRL Press, London.

Bressler, S.L. (1990). The gamma wave: a cortical information carrier. **Trends in Neuroscience, 13,** 5: 161-162

Broomhead, D.S., & King, G. (1986). Extracting qualitative dynamics from experimental data. **Physica, 20 D**: 217

Bruckner, L.A. (1978). Chernoff Faces. In Wang, P.C.C. (ed) **Graphical Representation of Multivariate Data.** Academic Press, New York.

Buchwald, J.S (1989). Comparisons of sensory and cognitive brain potentials in the Human and in an animal model. In: Basar, E., & Bullock, T.E. (eds) **Brain Dynamics: Progress and Perspectives**. Springer-Verlag, Berlin. 242-257

Buchwald, J.S (1990). Animal models of cognitive event-related potentials. In: Rohrbaugh, J.W., Parasurman, R., & Johnson Jnr, R.(eds) **Event-Related Brain Potentials, Basic Issues and Applications.** Oxford University Press. New York. 57-76

Buck, L., & Axel, R. (1991). A novel multigene family may encode odorant receptors: A molecular basis for odor recognition. **Cell, 65**: 175-187

Bullock, T.H. (1988). Compound potentials of the brain, ongoing and evoked: Perspectives from comparative neurology. In: Basar, E. (ed) **Dynamics of Sensory and Cognitive Processing by the Brain.** Springer-Verlag. Berlin. 3-19

Bullock, T.H. (1988). How brains may work: A view from comparative physiology. In: Basar, E. (1988) **Dynamics of Sensory and Cognitive Processing by the Brain**. Springer-Verlag, Berlin. 354-359

Bullock, T.H. (1989). Signs of dynamic processes in organised neural tissue: Extracting order from chaotic data. In: Basar, E., & Bullock, T.H. (eds). **Brain Dynamics: Progress and Perspectives.** Springer Verlag, Berlin: 539-547

Cain, W.S. (1982). Odor identification by males and females: predictions vs performance. **Chemical Senses, 7, 2:** 129-142

Carpenter, G.A., & Grossberg, S. (1987). Discovering order in chaos: Stable self-organisation of neural recognition codes. In: Koslow, S.H., Mandell, A.J., & Shlesinger, M.F. (eds) **Perspectives in Biological Dynamics and Theoretical Medicine.** Annals of the New York Academy of Sciences, Volume 504. New York: 33-51

Castellucci, V.F. (1985). The chemical senses: Taste and smell. In: Kandel, E.R., & Schwartz, J.H. (eds) **Principles of neural science.** Second edition, Elsevier, New York.

Cattarelli, M. (1989). Optical mapping of the olfactory system activity using voltage-sensitive dyes. In: Schild, D. **Chemosensory Information Processing**. Springer-Verlag, Berlin. 315-329

Chanel, J. (1987). The olfactory system as a molecular descriptor. **News Physiology Science, 2, Dec**: 203-208 (NIPS)

Chaput, M.A., & Holly, A. (1985). Responses of olfactory bulb neurons to repeated odour stimulation in awake, freely breathing rabbits. **Physiological Behaviour, 34**: 249-58

Chay, T.R., & Rinzel, J. (1985). Busting, beating and chaos in an excitable membrane model. **Biophysics Journal, 47**: 357-366

Clarke, J.W., Chen, J., & Kurten, K.E. (1989). Analog simulation of circuits in the olfactory bulb. In: Cotterhill, R.M.J. (ed) **Models of Brain Function**. Cambridge University Press. Cambridge.

Coburn, K.L., & Moreno, M.A. (1988). Facts and Artifacts in Brain Electrical Activity Mapping. **Brain Topography, 1, 1**: 37-45

Cooper, R. (1975). Measurement of Time and Phase Relationships of the EEG. In: Dolce, G., & Kunkel, H. **C.E.A.N. Computerised EEG Analysis,** Gustav Fischer Verlag, Stuttgart: 85-97

Cooper, R., Osselton, J.W., Shaw, J.C. (1974). **EEG Technology.** Butterworth & Co. London

Coppola, R. (1990). Topographic Mapping of Multilead Data. In: Rohrbaugh, J.W., Parasurman, R., & Johnson Jnr, R.(eds) **Event-Related Brain Potentials, Basic Issues and Applications.** Oxford University Press. New York. 37-44

Creutzfeldt, O.D., Bodenstein, G., Barlow, J.S. (1985). Computerised EEG pattern classification by adaptive segmentation and probibility density function classification: clinical evaluation. **EEG & Clinical Neurophysiology, 60:** 373-393

Crutchfield, J.P., Farmer, J.D., Packard, N.H., & Shaw, R.S. (1986). Chaos. **Scientific American, December, 255**: 38-49

Davis, D.R. (1983) Attention, arousal and effort. In: Gale, A., & Edwards, J.A. **Physiological correlates of human behaviour.** Volume two, Attention and Performance. Academic Press. London: 9-30

Dimond, S.J. (1977). Vigilance and split-brain research. In: Mackie, R.R. (ed) **Vigilance: Theory, operational performance, and physiological correlates**. Plenum Press. New York.

Dodd, G., & Van Toller, S. (1983). The biochemistry and psychology of perfumery. **Perfumer and Flavorist, 8, 4:** 1-14.

Dodd, G.H. (1988). The molecular dimension in perfumery. In: Van Toller, S., & Dodd, G.H. (eds) **Perfumery: The psychology and biology of fragrance**. Chapman and Hall, London.

Dolce, G., & Decker, H. (1975). Application of Multivariate Statistical Methods in Analysis of Spectral Values of the EEG. In: Dolce, G., & Kunkel, H. (eds). **CEAN: Computerised EEG Analysis.** Gustav Fischer Verlag, Stuttgart. 157-171

Dolce, G., & Kunkel, H. (1975). **CEAN: Computerised EEG Analysis.** Fischer Verlag. Stuttgart.

Doty, R.L. (1975). An examination of relationships between the pleasantness, intensity and concentration of 10 odorous stimuli. **Perception and Psychophysics, 17, 5:** 492-496

Doty, R.L. (1991). Olfactory system. Getchell, T.V., Doty, R.L., Bartoshuk, L.M., & Snow Jr, J.B. (eds) **Smell and taste in health and disease.** Raven Press, New York.

Duchamp-Viret, P., Duchamp, A., Vigoroux, M. (1989). Amplifying role of convergence in olfactory system: comparison of receptor cell and second order neuron sensitivities. **Journal of Neurophysiology, 61:** 1085-1094

Duffy, F.H. (1989). Topographical mapping of brain electrical activity: Clinical applications and issues. In: Maurer, K. (ed) **Topographic Mapping of EEG and Evoked Potentials.** Springer-Verlag. Berlin.

Duffy, F.H., & Maurer, K. (1989). Establishment of guidelines for the use of topographic mapping in clinical neurophysiology: A philosophical approach. In: Maurer, K. (ed) **Topographic Brain Mapping of EEG and Evoked-Potentials.** Springer-Verlag. Berlin.

Duffy, F.H., Burchfiel, J.L. & Lombroso, C.T. (1979). Brain electrical activity mapping (BEAM): A method for extending the clinical utility of EEG and evoked potential data. **Annals of Neurology, 5, 4:** 309-321

Duffy, F.H., McAnulty, G.B., & Schachter, S.C. (1984). Brain Electrical Activity Mapping. In: Geschwind, N., & Galitsarda, A.M. (eds) **Cerebral Dominance: The Biological Foundation.** Harvard University Press: 55-73

Dumermuth, G., Gasser, T., & Lange, B., (1975). Aspects of EEG Analysis in the Frequency Domain. In: Dolce, G., & Kunkel, H. (eds) **CEAN: Computerised EEG Analysis.** Fischer Verlag, Stuttgart : 429-457

Dunn, J.D., Cometto-Muniz, J.E., & Cain, W.S. (1982). Nasal reflexes: Reduced sensitivity to CO_2 irritation in cigarette smokers. **Journal of Applied Toxicology, 2, 3**: 176-178

Dvorak, I., Albrecht, V., & Holden, A.V. (1991). Brain functioning translated into mathematics. In Dvorak, I., & Holden, A.V. (eds) **Mathematical approaches to brain functioning diagnostics.** Manchester University Press, Manchester. 3-13

Engen, T., Gilmore, M.M., & Mair. R.G. (1991). Odour memory. In: Getchell,T.V., Doty, R.L., Bartoshuk, L.M., & Snow Jr, J.B. (eds) **Smell and taste in health and disease.** Raven Press, New York. 315-329

Engen.T. (1982). **The Perception of Odours**. Academic Press. New York.

Erdi, P. (1991). Self-organisation in the nervous system: Network structure and stability. In: Dvorak, I. & Holden, A.V. **Mathematical Approaches to Brain Functioning and Diagnostics.** Manchester University Press. Manchester. 31-45

Erikson, R.P. (1978). Common properties of sensory systems. In: Masterton, R.B., & Glendenning, (eds) **Handbook of Behavioural Neurobiology.** Plenum Press, New York.

Erikson, R.P. (1985). Grouping in the chemical senses. **Chemical Senses, 10, 3:** 333-340

Eskenazi, B., Cain, W.S., Novelly, R.A., & Friend, K.B. (1983). Olfactory functioning in temporal lobectomy patients. **Neuropsychologia, 21**: 365-374

Eskenazi, B., Cain, W.S., Novelly, R.A., & Mattson, R. (1986). Odor perception in temporal lobe epilepsy patients with and without temporal lobectomy. **Neuropsychologica, 24**: 553-562

Etenvon, P., Gaches, J., Debouzy, C., Gueguen, B. & Peron-Magnan, P. (1985). Electroencephalographic cartography. I. By means of mini- or micro-computers. Reliability and interest of this electrical non-invasive brain imagery. **Neuropsychobiology, 13:** 69-73

Eysenck, M.W. (1983) Arousal & attention. In: Gale, A., & Edwards, J. (eds). **The EEG and Human Behaviour.**

Eysenck, M.W. (1984). **A handbook of cognitive psychology.** Lawrence Erlbaum Associates. London.

Farbman, A.I. (1990). Olfactory neurogenesis: genetic or environmental controls ? **Trends in Neurosciences, 13, 9**: 362-365

Freeman, W.J. (1975). **Mass Action in the Nervous System**. Academic Press. New York.

Freeman, W.J. (1979). EEG analysis gives model of neuronal template-matching mechanism for sensory search with olfactory bulb. **Biol.Cybern, 35**: 221-234

Freeman, W.J. (1981). A physiological hypothesis of perception. **Perspectives Biol.Med, 24**: 561-592

Freeman, W.J. (1984). A watershed in the study of nonlinear neural dynamics. In: Basar, E. (ed) **Dynamics of Sensory and Cognitive Processing by the brain**. Springer-Verlag. Berlin. 378-381

Freeman, W.J. (1985). Nonlinear neural dynamics in olfaction as a method for cognition. In: Basar, E.(ed) **Dynamics of Sensory and Cognitive Processing by the Brain**. Springer-Verlag. Berlin. 19-30

Freeman, W.J. (1985). Overview of methodology. In: Basar, E. (ed) **Dynamics of Sensory and Cognitive Processing by the brain.** Springer-Verlag. Berlin. 385-395

Freeman, W.J. (1987). Analytic techniques used in the search for the physiological basis of the EEG. In: Gevins, A.S & Remond, A. (eds) **Handbook of Electroencephalography and Clinical Neurophysiology: Methods of Analysis of Brain Electrical and Magnetic Signals**, Volume 1, Elsevier, Amsterdam. 583-665

Freeman, W.J. (1989). Analysis of strange attractors in EEGs with kinesthetic experience and 4D computer graphics. In: Basar, E., & Bullock, T.H. (1989). **Brain Dynamics: Progress and Perspectives.** Springer Verlag, Berlin. 512-520

Freeman, W.J. (1991a). Nonlinear dynamics in olfactory information processing. In: Davis, J.L., & Eichenbaum, H. (eds) **Olfaction: A model system for computational Neuroscience.** A Bradford Book, The MIT Press, Cambridge, Massachussetts: 225-250

Freeman, W.J. (1991b). The physiology of perception. **Scientific American, February**: 34-41

Freeman, W.J., & Davis, G.W. (1990). Olfactory EEG changes under serial discrimination of odorants by rabbits. In: Schild, D. (ed) **Chemosensory Information Processing**. Springer-Verlag, Berlin. 375-393

Freeman, W.J., & Grajski, K.A. (1987). Non-linear spatio-temporal dynamics of olfactory EEG in behaviour. **Society for Neuroscience Abstracts, 13, 2:** 1401

Freeman, W.J., & Maurer, K. (1989). Advances in brain theory give new directions to the use of the technologies of brain mapping in behavioural studies. In: Maurer, K.

(ed) **Topographic Brain Mapping of EEG and Evoked-Potentials.** Springer-Verlag. Berlin.

Freeman, W.J., & Skarda, C.A. (1985). Nonlinear dynamics, perception and the EEG; The neo-Sherringtonian view. **Brain Research, 10**: 147-175

French, C.C., & Beaumont, G. (1984). A Critical Review of EEG Coherence Studies of Hemispheric Function. **International Journal of Psychophysiology, 1:** 241-254

Frye, R.E., Schwartz, B.S., & Doty, R.L. (1990). Dose related effects of cigarette smoking on olfactory function. **Journal of the American Medical Association, 263, 9:** 1233-1236

Gale, A. (1977). Some EEG correlates of sustained attention. In: Mackie, R.R. (ed) **Vigilance: Theory, operational performance, and physiological correlates**. Plenum Press. New York. 263-285

Gale, A., & Edwards, J. (1983). **The EEG and Human Behaviour.**

Gersch, W. (1987) Non-stationary multichannel time series analysis. In: Gevins, A.S., & Remond, A. (eds). **Handbook of Electroencephalography and Clinical Neurophysiology: Methods of Analysis of Brain Electrical and Magnetic Signals.** Volume 1. Elsevier, Amsterdam. 261-285

Geschwind, N., & Levitsky, W. (1968). Human brain: Left-right asymmetries in temporal speech regions. **Science, 161**: 186-187

Getchell, M.L., & Mellert, T.K. (1991). Olfactory mucus secretion. In: Getchell,T.V., Doty, R.L., Bartoshuk, L.M., & Snow Jr, J.B. (eds) **Smell and taste in health and disease.** Raven Press, New York. 83-97

Getchell, T.V., Doty, R.L., Bartoshuk, L.M., & Snow Jr, J.B. (1991) **Smell and taste in health and disease.** Raven Press, New York.

Getz, W.M. (1991). A neural network for processing olfactory-like stimuli. **Bulletin of Mathematical Biology, 6**: 805-823

Gevins, A.S. (1981). The use of brain electrical potentials (BEP) to study localisation of human brain function. **International Journal of Neuroscience, 13**: 27-41

Gevins, A.S. (1985). Recent advances in neurocognitive pattern analysis. In: Basar, E. (ed) **Dynamics of Sensory and Cognitive Processing by the brain**. Springer-Verlag. Berlin. 88-103

Gevins, A.S. (1987a). Obstacles to progress. In: Gevins, A.S., & Remond, A. (eds). Handbook of **Electroencephalography and Clinical Neurophysiology: Methods of Analysis of Brain Electrical and Magnetic Signals.** Volume 1. Elsevier, Amsterdam.

Gevins, A.S. (1987b). Overview of computer analysis. In: Gevins, A.S., & Remond, A. (eds). **Handbook of Electroencephalography and Clinical Neurophysiology: Methods of Analysis of Brain Electrical and Magnetic Signals.** Volume 1. Elsevier, Amsterdam: 31-75

Gevins, A.S. (1987c). Statistical pattern recognition. In: Gevins, A.S., & Remond, A. (eds). **Handbook of Electroencephalography and Clinical Neurophysiology: Methods of Analysis of Brain Electrical and Magnetic Signals**. Volume 1. Elsevier, Amsterdam: 541-582

Gevins, A.S. (1990). Dynamic Patterns in Multiple Lead Data. In: Rohrbaugh, J.W., Parasurman, R., & Johnson Jnr, R.(eds) **Event-Related Brain Potentials, Basic Issues and Applications.** Oxford University Press. New York: 44-57

Gevins, A.S., & Remond, A. (1987). **Handbook of Electroencephalography and Clinical Neurophysiology: Methods of Analysis of Brain Electrical and Magnetic Signals**. Volume 1. Elsevier, Amsterdam.

Gevins, A.S., & Schaffer, R.E. (1980). A Critical Review of Electroencephalogram (EEG) correlates of higher cortical functions. CRC, **Critical Review in Bioengineering, 4**: 113-164

Gleick, J. (1988) **Chaos.** William Heinmann Ltd. London

Goldberg, E., & Costa, L.D. (1981). Hemispheric differences in the acquisition and use of descriptive systems. **Brain and Language, 14**: 144-173

Goldberger, A.L., Rigney, D.R., & West, B.J. (1990). Chaos and fractals in human physiology. **Scientific American, February, 262, 2**: 34-42

Greer, C.A. (1991). Structural Organisation in the Olfactory System. In: Getchell,T.V., Doty, R.L., Bartoshuk, L.M., & Snow Jr, J.B. (eds) **Smell and taste in health and disease.** Raven Press, New York. 65-83

Grusser, O.-J. (1989). In: Basar, E., & Bullock, T.H. (eds). **Brain Dynamics: Progress and Perspectives.** Springer Verlag, Berlin: 484-487

H & R (1985). The H & R book of perfume. Understanding fragrance: origin, history, develpoment, meaning. (ed) Muller, J. Johnson Publishing, London.

Haberly, L.B. (1985). Neuronal circuitry in olfactory cortex: anatomy and functional implications. **Chemical Senses, 10, 2**: 219-238

Haberly, L.B., & Bower, J.M. (1989). Olfactory cortex: Model circuit for study of associative memory ? **Trends in Neurosciences, 12, 7**: 258-264

Halasz, N. (1989). Morphological basis of information processing in the olfactory bulb. In: Schild, D. **Chemosensory Information Processing**. Springer-Verlag, Berlin. 175-191

Hawkins, J.M. (1991). (ed) **The Oxford Reference Dictionary.** Clarendon Press. Oxford.

Hess, B., & Marcus, M. (1987). Order and choas in biochemistry. **Trends in Biochemical Sciences, 12**: 45-48

Hines, D.E. (1977). Olfaction and the right cerebral hemisphere. **Journal of Altered States of Consciousness, 3, 1**: 47-59

Hjorth, B. (1975). An on-line transformation of EEG scalp potentials in orthogonal source derivations. **Electroencephalography and Clinical Neurophysiology, 39**: 526-530

Holley, A. (1991). Neural coding of olfactory information. In: Getchell,T.V., Doty, R.L., Bartoshuk, L.M., & Snow Jr, J.B. (eds) **Smell and taste in health and disease.** Raven Press, New York. 329-345

Holley, A., & Duchamp-Viret, P. (1989). Single cell activities and the olfactory code. In: Schild, D. (ed) **Chemosensory Information Processing**. Springer-Verlag, Berlin. 235-247

Howells, P. (1992). An empirical study of cortical EEG responses to olfactory stimuli using multidimensional analyses. **Submitted for the Degree of M.Phil,** University of Warwick

International Federation of Societies for EEG and Clinical Neurophysiology. (1961). The 10/20 Electrode System. **EEG and Clinical Neurophysiology, 1:** 13-19

Jansen, B.H. (1991). Quantitative analysis of electroencephalograms: Is there chaos in the future ? **International Journal of Biomedical Computing, 27**: 95-123

Jasper, H. (1958). Report of the committee on methods of clinical exam in EEG. **Electroencephalography and Clinical Neurophysiology, 10**: 370-375

Jennings, J.R., Cohen, M.J., Ruchkin, D.S., & Fridlund, A.J. (1987). Methodology: Editorial Policy on Analyses of Variance with Repeated Measures. **Psychophysiology, 24, 4:** 474-486

John, E.R. (1972). Switchboard vs statistical theories of learning and memory. **Science, 177**: 850-864

John, E.R., Harmony, T., & Valdes-Sosa. (1987). The use of statistics in electrophysiology. In: Gevins, A.S & Remond, A. (eds) **Handbook of Electroencephalography and Clinical Neurophysiology: Methods of Analysis of Brain Electrical and Magnetic Signals**, Volume 1, Elsevier, Amsterdam. 497-506

Jones-Gotman, M., & Zatorre, R.J. (1988). Olfactory identification deficits in patients with focal cerebral excision. **Neuropsychologia, 26, 3**: 387-400

Kahn, E.M., Weiner, R.D., Brenner, R.P., & Coppola, R. (1988). Topographic maps of brain electrical activity: Pitfalls and precautions. **Biol. Psychiatry, 23**: 628-636

Kamp, A., & Lopes da Silva, F. (1987a). Polygraphy. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 45-55

Kamp, A., & Lopes da Silva, F. (1987b). Technological Basis of EEG Recording. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 45-55

Kanamura, S. (1990). The relation between brain waves and emotion during presentation of various odors. **Chemical Senses, Aug 90,** JASTS XXIII Abstr.

Kanamura, S., Kiyota, S., Takashima, Y., Kanisawa, T., Indo, M., Loveren, G.V., Kukuda, H., & Torrii, S. (1989). Effects of odors on CNV. IV. Abstract in: **Chemical Senses, 14, 2.**

Kandel, E.R., & Schwartz, J.H. (1985). **Principles of neural science.** Second edition, Elsevier, New York.

Katznelson, R.D. (1981). EEG recording, electrode placement and aspects of generator localisation. In: Nunez, P.L. (ed) **Electric Fields of the Brain.** Oxford University Press. New York. 176-214 and 401-437

Kauer, J.S. (1991). Contributions of topography and parallel processing to odor coding in the vertebrate olfactory pathway. **Trends in Neurosciences, 14, 2**: 79-85

Kauer, J.S., (1980). Some spacial characteristics of information processing in the vertebrate olfactory pathway. In : (ed) H.van der Starre. **Olfaction and Taste VII.** IRL Press, London, 227-236.

Kelly, J.P. (1985). Anatomical basis of sensory perception and motor coordination. In: Kandel, E.R., & Schwartz, J.H. (eds) **Principles of neural science.** Second edition, Elsevier, New York. 222-243

Kendal-Reed, M. (1990). Human infant olfaction: responses to food odours measured by brain electrical activity mapping (BEAM). **PhD Thesis.** University of Warwick.

Kendal-Reed, M., & Van Toller, S. (1989). Brain electrical activity mapping (BEAM) in infants presented with food odours. Abstract in: **Chemical Senses, 14, 2.**

Ketchum, K.L., & Haberly, L.B. (1991). Fast oscillations and dispersive propagation in olfactory cortex and other cortical areas: A functional hypothesis. In: Davis, J.L., & Eichenbaum, H. (eds) **Olfaction: A model system for computational Neuroscience.** A Bradford Book, The MIT Press, Cambridge, Massachussetts: 69-100

Klemm, W.R., Lutes, S.D., Hendrix, D.V., & Warrenburg, S. (1992). Topographical EEG maps of human responses to odours. **Chemical Senses, 18:** 347-361

Knott, P. (1976). The theta rhythm. In: Remond, A. (ed) **The Handbook of Electroencephalography and Clinical Neurophysiology,** Vol.6A. Elsevier. Amsterdam.

Kobal, G. & Hummel, T. (1988). Cerebral chemosensory evoked potentials elicited by chemical stimulation of the human olfactory and respiratory nasal mucosa. **Electroencephalography and Clinical Neurophysiology, 71:** 241-250.

Kobal, G., & Hummel, T. (1989). Scalp distribution of chemosensory evoked potentials elicited by trigeminal and olfactory stimuli. Abstract in: **Chemical Senses, 14, 2.**

Kobal, G., & Hummel, T. (1991). Olfactory evoked potentials in humans. In: Getchell, T.V., Doty, R.L., Bartoshuk, L.M., & Snow, Jnr, J.B. (eds) **Smell and Taste in Health and Disease.** Raven Press. New York. 255-277

Kobal, G., & Shepherd, B. (1990). The Human Olfactory Evoked Response. **Journal of Neurology, 37, Suppl. 1:** 592

Kobal, G., Van Toller, S., & Hummel, T. (1989). Is there directional smelling ? **Experientia, 45:**130-132

Labows, J.N., & Wysocki, C.J. (1984). Individual differences in odor perception. **The Perfumer & Flavorist, 9:** 21-26

Layne, S.P., Mayer-Kress, G., & Holzfuss, J. (1985). Problems associated with dimensional analysis of EEG data. In: Meyer-Kress, G. (ed). **Dimensions and Entropies in Chaotic Systems.** Springer Verlag, Berlin: 246-255

Lehman, D. (1989). From mapping to the analysis and interpretation of EEG / EP maps. In: Maurer, K. (ed) **Topographic Mapping of EEG and Evoked Potentials**. Springer-Verlag. Berlin.

Lehman, D., Brandeis, D., Ozaki, H., & Pal, I. (1987). Human brain EEG fields: Micro-states and their functional significance. In: Haken, H. (ed) **Computational systems - Natural and artificial.** Springer-Verlag. Berlin. 65-74

Lehmann, D. (1975). EEG Phase Differences and their Physiological Significance in Scalp Field Studies. In: Dolce, G., & Kunkel, H. (eds) **CEAN: Computerised EEG Analysis.** Fischer Verlag, Stuttgard: 102-110

Lehmann, D. (1984). EEG assessment of brain activity: spatial aspects, segmentation and imaging. International **Journal of Psychophysiology, 1:** 267-276.

Li, Z. (1991). A Model of Olfactory Adaptation and Sensitivity Enhancement in the Olfactory Bulb. **Biological Cybernetics, 62**: 349-361

Linke, D.B., Reuter, B.M., & Kurthen, M. (1989). Brain lateralisation in stress reactions. In: Maurer, K. (ed) **Topographic Mapping of EEG and Evoked Potentials**. Springer-Verlag. Berlin. 326-327

Lopes da Silva, F. (1987a). Dynamics of EEG's as Signals of Neural Populations: Models and Theoretical Considerations. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields**. Urban and Shwarzenberg: 16-28

Lopes da Silva, F. (1987b). EEG Analysis: Theory and Practice. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 871-897

Lopes da Silva, F. (1987c). Event related potentials: Methodology and Quantification. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 763-772

Lopes da Silva, F.H., & Mars, N.J.I (1987). Parametric methods in EEG analysis. In Gevins, A.S., & Remond, A. (eds). **Handbook of Electroencephalography and Clinical Neurophysiology: Methods of Analysis of Brain Electrical and Magnetic Signals**. Volume 1. Elsevier, Amsterdam. 243-257

Lorig, T. S., Huffman, E., DeMartino, A., & De Marco, J. (1991). The effects of low concentration odors on EEG activity and behaviour. **Journal of Psychophysiology, 5:** 69-77

Lorig, T.S. & Schwartz, G.E. (1988). Brain and odor I. Alteration of EEG by odor administration. **Psychobiology, 16 3:** 281-284.

Lorig, T.S. & Schwartz, G.E. (1988). EEG activity during relaxation and food imagery. **Imagination, Cognition and Personality, 8:** 201-208

Lorig, T.S. & Schwartz, G.E., & Herman, K.B., & Lane, R.D. (1988). Brain and odor II. EEG activity during nose and mouth breathing. **Psychobiology, 16 (3),** 285-287.

Lorig, T.S. (1984). Period analysis of the EEG by 6502-based microcomputer. **Behavior Research Methods, Instruments & Computers, 16, 3:** 331-332.

Lorig, T.S. (1986) EEG and task performance: a comparison of three analytic techniques. **Physiological Psychology, 14, (3&4):**130-132

Lorig, T.S. (1989). Human EEG and Odor Response. **Progress in Neurobiology, 33:** 387-398

Lorig, T.S. (1991). The effects of low concentration odors on EEG activity and behavior. **Journal of Psychophysiology, 5:** 69-77

Lorig, T.S., & Roberts, M. (1990). Odor and cognitive alteration of the contingent negative variation. **Chemical Senses, 15, 5:** 537-545

Lorig, T.S., & Schwartz, G.E. (1990). Factor analysis of the EEG indicates inconsistencies in traditional bands. **Journal of Psychophysiology, 3:** 369-375

Lorig, T.S., Herman, K.B., Schwartz, G.E., & Cain,W.S. (1990). EEG activity during the administration of low concentration odours. **Bulletin of the Psychonomic Society, 28:** 405-408

Low, M.D. (1987). Psychology, Psychophysiology and the EEG. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 541-548

Mackay, D.M. (1984). Source density mapping of human visual receptive fields using scalp electrodes. **Experimental Brain Research, 54**: 579-581

Mackey, M.C., & Milton, J.G. (1987). Dynamical Diseases. In: Koslow, S.H., Mandell, A.J., & Shlesinger, M.F. (eds) **Perspectives in Biological Dynamics and Theoretical Medicine.** Annals of the New York Academy of Sciences, Volume 504. New York.

Makin, J.W., & Porter, R.H. (1989). Attractiveness of Lactating Females Breast Odours to Neonates. **Child Development, 60**: 803-810

Martin, J.H. (1985). Cortical neurons, the EEG and mechanisms of epilepsy. In: Kandel, E.R., & Schwartz, J.H. (eds) **Principles of neural science.** Second edition, Elsevier, New York. 636-647

Masterton, R.B., & Glendenning, K.K. (1978). Phylogeny of the vertebrate sensory systems. In: Masterton, R.B., & Glendenning, K. K (eds) **Handbook of Behavioural Neurobiology.** Plenum Press, New York.

Matousek, M. (1991). EEG brain mapping: Trails and errors. In: Dvorak, I. & Holden, A.V. **Mathematical Approaches to Brain Functioning and Diagnostics.** Manchester University Press. Manchester. 171-183

Matsuura, M., Yamamoto, K., Fukuzawa, H., Okubo, Y., Uesugi, H., Moriiwa, M., Kojima, T., & Shmazono, Y. (1985). Age development and sex differences of various EEG elements in healthy children and adults: Quantification by a computerised waveform recognition model. **Electroencephalography and Clinical Neurophysiology, 60**: 394-406

Maus, A., & Endressen, J. (1979). Misuse of Computer Generated Results. **Medical and Biological Engineering and Computing, 17:** 126-129

May, R. (1987). Nonlinearities and complex behaviour in simple ecological and epidemiological models. In: Koslow, S.H., Mandell, A.J., & Shlesinger, M.F. (eds) **Perspectives in Biological Dynamics and Theoretical Medicine.** Annals of the New York Academy of Sciences, Volume 504. New York.

Mayer-Kress, G., Barczys, C., & Freeman, W.J. (1991). Attractor reconstruction from event-related multi-electrode EEG data. In: Dvorak, I. & Holden, A.V. **Mathematical Approaches to Brain Functioning and Diagnostics.** Manchester University Press. Manchester. 315-337

Meyer-Kress, G. (1985). Introductory Remarks. In: Meyer-Kress, G. (ed) **Dimensions and Entropies in Chaotic Systems.** Springer Verlag, Berlin.

Meyer-Kress, G., & Holzfuss, J. (1985). Analysis of the Human Electroencephalogram with Methods from Nonlinear Dynamics. In: Meyer-Kress, G. (ed) **Dimensions and Entropies in Chaotic Systems,** Springer Verlag, Berlin

Moncrieff, R.W. (1962). Effect of odours on EEG records. **Perfumery & Essential Oil Record, 53**: 757-760, 825-828

Morihisa, J.M (1985) Computerised Topographic Mapping of Electrophysiological Data in Psychiatry. **Psychiatric Annals, 15, 4**: 250-253

Morrison, E.E., & Costanzo, R.M. (1990) Morphology of the Human Olfactory Epithelium. **Journal of Comparative Neurology, 297:** 1-13

Moulton, D.G. (1978). Olfaction. In: Masterton, R.B., & Glendenning, (eds) **Handbook of Behavioural Neurobiology.** Plenum Press, New York.

Mpitsos, G.J. (1989). Chaos in Brain Function and the Problem of Nonstationarity: A Commentary. In: Basar, E., & Bullock, T.E. (eds) **Brain Dynamics: Progress and Perspectives**. Springer-Verlag, Berlin.

Muller, B., & Reinhardt, J. (1990). **Neural networks: An introduction**. Springer-Verlag. Berlin.

Nicolis, J.S. (1985). Chaotic Dynamics of Information Processing with Relevance to Cognitive Brain Functions. **Kybernetes, 14:** 167-172

Nicolis, J.S. (1987). Chaotic dynamics in biological information processing: A heuristic outline. In: Degn, H., & Holden, A.V. **Chaos in Biological Systems**. Plenum Press. New York. 221-232

Niedermeyer, E. (1987). EEG Patterns and Genetics. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 159-162

Niedermeyer, E. (1987a). The Normal EEG of the Waking Adult. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 97-117

Niedermeyer, E. (1987b). Electrocorticography. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 613-617

Norris, D. (1991). The constraints on connectionism. **The Psychologist: Bulletin of the British Psychological Society, 4**: 293-296

Nunez, P.L. (1981). **Electric Fields of the Brain.** Oxford University Press. New York

Nunez, P.L. (1990). Physical principles and neurophysiological mechanisms underlying event related potentials. In: Rohrbaugh, J.W., Parasuraman, R., & Johnson jr, R. (eds) **Event-related Brain Potentials: Basic Issues and Applications.** Oxford University Press. New York. 19-37

Offenloch, K. (1975). What is the EEG composed of? Aspects of EEG electrogenesis. In: Dolce, G., & Kunkel, H. (eds) **CEAN: Computerised EEG Analysis.** Fischer Verlag, Stuttgart: 71-110

Oken, B.S., & Chiappa.K.H. (1986). Statistical issues concerning the computer analysis of brainwave topography. **Annals of Neurology, 19**: 493-494

Petsche, H. (1989). From Grapheim to Topos: Past and future of brain mapping. In: Maurer, K. (ed) **Topographic Mapping of EEG and Evoked Potentials**. Springer-Verlag. Berlin.

Petsche, H., Pockberger, H., & Rappelsberger, P. (1988). Cortical strucure and electrogenesis. In: Basar, E. (ed). **Dynamics of Sensory and Cognitive Processing by the Brain**. Springer-Verlag. Berlin. 123-140

Pockberger, H., Rappelsberger, P., & Petsche, H. (1988). Cognitive Processing in the EEG. In: Basar, E. (1988) **Dynamics of Sensory and Cognitive Processing by the brain**. Springer-Verlag. Berlin. 266-275

Potter, H., & Butters, N. (1980). An assessment of olfactory deficits in patients with damage to prefrontal cortex. **Neuropsychologica, 18**: 621-8

Pritchard, W.S., & Duke, D.W. (1991). Modulation of EEG dimensional complexity by smoking. **Journal of Psychophysiology, 6**: 1-10

Pritchard, W.S., Duke, D.W., & Coburn, K.L. (1991). Altered EEG dynamical responsivity associated with normal aging and probable Alzheimer's disease. **Dementia**, 63: 1-7

Rappelsberger, P., & Petsche, H. (1988). Probability Mapping: Power and Coherence Analysis of Cognitive Processes. **Brain Topography, 1, 1**: 46-54

Rausch, R., & Serafentindes, E.A. (1975). Specific alterations of olfactory function in humans with temporal lobe lesions. **Nature, 255**: 557-8

Rebert, C.S. (1980). Neurobehavioural aspects of brain slow potentials. **Progress in Brain Research, 54**: 381-402.

Reilly, E.L. (1987). EEG Recording and Operation of the Apparatus. In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 57-77

Richardson, J.T.E. & Zucco, G.M. (1989). Cognition and Olfaction: A Review. **Psychology Bulletin, 105, 3**: 352-360

Rohrbaugh, J.W., Parasurman, R., & Johnson Jnr, R.(1990) **Event-Related Brain Potentials, Basic Issues and Applications.** Oxford University Press, New York.

Roschke, J., & Basar, E. (1988). The EEG is not simple noise: Strange attractors in intercranial sources. In: Basar, E. (1988) **Dynamics of Sensory and Cognitive Processing by the brain**. Springer-Verlag, Berlin: 203-219

Schild, D. (1990). **Chemosensory Information Processing**. Springer-Verlag. Berlin.

Semmes, J. (1968). Hemispheric specialisation: A possible clue to mechanism. **Neuropsychologica, 6:** 11-26

Shannon, C.E., & Weaver, H. (1949). **The mathematical theory of communication**. University of Illinois Press, New York.

Shaw, J.C. (1981). An Introduction to the Coherence Function and its use in EEG Signal Analysis. **Journal of Medical Engineering and Technology, 5, 6:** 279-288

Shaw, J.C. (1984). Correlation and Coherence Analysis of the EEG: A Selective Tutorial Review. **International Journal of Psychophysiology, 1:** 255-266

Shaw, J.C., O'Connor, K., & Ongley, C. (1978). EEG coherence as a measure of cerebral functional organisation. In: Brazier, M.A.B., & Petsche, H. (eds). **Architecture of the cerebral cortex.** Raven Press, New York. 245-255

Sheer, D.E. (1984). Focused arousal, 40-Hz EEG, and dysfunction. In Elbert, Th., Rockstroh, B., Lutzenberger, W., & Birbaumer, N. (eds). **Self regulation of the brain and behaviour.** Springer Verlag, Berlin. 64-85

Sheer, D.E. (1989). Sensory and cognitive 40 Hz event-related potentials: Behavioural correlates, brain function and clinical application. In: Basar, E., & Bullock, T.H. (1989). **Brain Dynamics: Progress and Perspectives.** Springer Verlag, Berlin. 339-374

Shepherd, G.M. (1972). Synaptic organisation of the mammalian olfactory bulb. **Physiology Review, 52:** 864-917

Shepherd, G.M. (1981). **Brain mechanisms of sensation.** In: Katsuki, Y., Norgren, R., & Sato, M. M. (eds) Wiley, New York: 209-223

Shepherd, G.M. (1991). Computational structure of the olfactory system. In: Davis, J.L., & Eichenbaum, H. (eds) **Olfaction: A model system for computational**

Neuroscience. A Bradford Book, The MIT Press, Cambridge, Massachussetts: 3-42

Sherrington, C.S. (1946). **Man and his nature.** Cambridge University Press. London.

Sicard, G. (1989). Receptor selectivity and dimensionality of odours at the stage of olfactory receptor cells. In: Schild, D. **Chemosensory Information Processing.** Springer-Verlag, Berlin. 21-33

Skarda, C. & Freeman, W.J. (1987). How brains make chaos in order to make sense of the world. **Behavioral and Brain Sciences, 10**: 161-195

Skarda, C.A. (1986). Explaining Behaviour: Bringing the Brain Back In. **Inquiry, 29:** 187-202

Skinner, J.E. (1984). Central gating mechanisms that regulate event-related potentials and behaviour. In Elbert, Th., Rockstroh, B., Lutzenberger, W., & Birbaumer, N. (eds). **Self regulation of the brain and behaviour.** Springer Verlag, Berlin. 42-59

Skinner, J.E., Martin, J.L., Landisman, C.E., Mommer, M.M., Fulton, K., Mitra, M., Burton, W.D., & Saltzberg, B. (1989). In: Basar, E., & Bullock, T.E. (eds) **Brain Dynamics: Progress and Perspectives**. Springer-Verlag, Berlin.

Soong, A.C.K., & Stuart, C.I.J.M. (1989). Evidence of chaotic dynamics underlying the human alpha-rhythm EEG. **Biological Cybernetics, 62**: 55-62

Stewart, I. (1989). **Does God Play Dice ? The New Mathematics of Chaos.** Pengiun. London

Stoddart, D.M. (1990). **The scented ape: The biology and culture of human odour.** Cambridge University Press, Cambridge.

Sugano, H. (1989). Effects of odors on mental functions. Abstract in: **Chemical Senses, 14, 2**: 303-326 (2)

Swenson, R.A., & Tucker, D.M. (1983). Multivariate analysis of EEG coherence: Stability of the metric, individual differences in patterning and response to arousal. **Biological Psychology, 17:** 59-75

Szentagothai, J., & Arbib, M.A. (1975). **Computational Models of Neural Organisation.** M.I.T Press, New York.

Tagaki, S.F. (1989a). **Human Olfaction.** University of Tokyo Press. Japan.

Tagaki, S.F. (1989b). Standard Olfactometries in Japan; A Review Over Ten Years. **Chemical Senses, 14, 1:** 25-46

Tecce, J.J., & Cattenach, L. (1987). Contingent Negative Variation (CNV). In: Niedermeyer, E., & Lopes da Silva, F. (eds) **Electroencephalography: Basic Principles, Clinical Applications and Related Fields.** Urban and Shwarzenberg: 657-671

Thatcher, R.W., & John, E.R. (1977). **Foundations of Cognitive Processes**. Lawrence Erlbaum Associates. New York.

Theiler, J. (1990). Estimating the fractal dimension of chaotic time series. **Lincoln Laboratory Journal,** 3: 63-86

Torrii, S.F.H., Kanemoto, H., Miyanchi, R., Hamauzu, Y., & Kawasaki, M. (1988). Contingent Negative Variation (CNV) and the psychological effects of odour. In: Van Toller, S., & Dodd, G. (eds). **Perfumery: the Psychology and Biology of Fragrance.** Chapman Hall. London. Chpt 6

Tucker, D.M. (1990). Asymmetries of neural architecture and the structure of emotional experience. In: Rohrbaugh, J.W., Parasurman, R., & Johnson Jnr, R.(eds)

Event-Related Brain Potentials, Basic Issues and Applications. Oxford University Press. New York. 130-145

Tucker, D.M., & Williamson, P.A. (1984). Asymmetrical neural control systems in human self-regulation. **Psychological Review, 91**: 185-215

Tukey, A. (1977). Exploratory Data Analysis. Addison-Wesley. Reading.

Van Drongelen, W. (1978). Unitary recordings of near threshold responses of receptor cells in the mucosa of the frog. **Journal of Physiology, (London) 227**: 423-435

Van Toller, C. (1985). Odours and Emotion. **Report prepared for PPF International** (now Quest International).

Van Toller, C., Kirk-Smith, M., Sleight, D., Wood, N., & Lombard, J. (1980). Hemispheric processing of odours. **Biological Psychology, 11, 3-4:** 262.

Van Toller, C., Kirk-Smith, M., Wood, N., Lombard, J., & Dodd, G.H. (1983). Skin conductance and subjective assessments associated withthe odour of 5-alpha-androstan-3-one. **Biological Psychology, 16:** 85-107.

Van Toller, S. (1987). Brain electrical activity mapping during the smelling of odours and trigeminal stimulants. **Psychophysiology (SPR Abstracts), 24, 5,** 619.

Van Toller, S. (1988). Emotion and the Brain. In: Van Toller, S., & Dodd, G. (eds). **Perfumery: the Psychology and Biology of Fragrance.** 121-140

Van Toller, S. (1991). The application of EEG measurements to the study of sensory responses to odours. **Trends in Food Science and Technology,** July: 173-175

Van Toller, S., & Dodd, G. (1988). **Perfumery: the Psychology and Biology of Fragrance.** Chapman Hall. London.

Van Toller, S., & Kendal-Reed, M. (1989). Brain Electrical Activity Topographical Maps Produced in Response to Olfactory and Chemosensory Stimulation. **Psychiatry Research, 29:** 429-430

Van Toller, S., Hotson, S., & Kendal-Reed, M. (1992). The brain and the sense of smell: Can we begin to make sense of the cortical information after an odour has been received ? In: Van Toller,S., & Dodd, G. (eds) **Fragrance: The Psychology and Biology of Perfume**. Elsevier. London.

Van Toller, S., Kendal-Reed, M., & Sleight, D. (1989). EEG activity to olfactory and chemosensory stimulation. Abstract in: **Chemical Senses, 14:** 2

Van Toller, S., Kendal-Reed, M., Sleight, D., & Behan, J. (1987). Brain electrical activity mapping (BEAM) during olfactory and chemosensory stimulation. **Research report, issued by private circulation**. University of Warwick.

Van Toller,C. (1987). Odours, emotion and psychophysiology. Paper presented at the Joint Symposium of the British Society of Perfumers and the Society of Cosmetic Scientists. In: **International Journal of Cosmetic Science 10:** 171-197

Vasey, M.W., & Thayer, J.F. (1987). Repeated Measures ANOVA in Psychophysiology. A Multivariate Solution. **Psychophysiology, 24, 4**: 479-487

Vogt, R.G., Rybczynski, R., & Lerner, M.R. (1989). The biochemistry of odorant reception and transduction. In: Schild, D. **Chemosensory Information Processing**. Springer-Verlag, Berlin. 33-77

Walter, D.O., Etenvon, P., Pidoux, B., Tortat, D. & Guillou, S. (1984). Computerised topo-EEG spectral maps: Difficulties and perspectives. **Neuropsychobiology, 11:** 264-272.

Westmoreland, B., & Klass, O.W. (1981). A distinctive rhythmic discharge in adults. **EEG and Clinical Neurophysiology, 51:** 186-191

Wilkinson, L. (1989). SYSTAT: The system for statistics. Evanston, IL: SYSTAT, Inc.

Wong, P.K.H. (1991). Introduction to Brain Topography. Plenum Press. New York.

Zatorre, R.J., & Jones-Gotman, M. (1990). Right-nostril advantage for discrimination of odors. **Perception & Psychophysics, 47, 6**: 526-531

Zatorre, R.J., & Jones-Gotman, M. (1991). Human Olfactory Discrimination after Unilateral Frontal or Temporal Lobectomy. **Brain, 114:** 71-84

Zucco, G.M., & Tressoldi, P.E. (1988). Hemispheric Differences in Odour Recognition. **Cortex, 25:** 607-615

Table of Contents, Appendices

Appendix 1- Background information

Structure and function in olfaction - receptor level

An important feature of most sensory systems is that they consist of serial chains of neurons that link the periphery with the spinal cord, brain stem, thalamus and neocortex. Olfaction is unique in that its projections travel first to the phylogenetically older portions of the cerebral cortex (the olfactory cortex) before progressing to the thalamus and neocortex. This section will concentrate on which aspects of the olfactory experience are analysed by structures at the different levels of the brain. A significant debate in odour perception has been about the role of the peripheral nervous system (Vogt, Rybczynski & Lerner, 1989). Therefore great consideration will be given to the type of neuronal coding that occurs at each level in the olfactory system, in order to establish what sort of information may reach the outer layers of the cortex to be captured by electroencephalographic techniques.

The division of the olfactory system into clear anatomical landmarks allows a discussion of each in turn. The olfactory epithelium and the olfactory bulb will be discussed here.

Olfactory transduction occurs in the olfactory epithelium located high in the nasal cavity. The olfactory epithelium in humans occupies only a small area of the cavity, approximately 5 cm^2; the remainder is taken up with respiratory epithelium. Inspired air containing odour molecules is drawn into the nose, the air is warmed and partly humidified and any particles are removed by the hairs and the respiratory epithelium before it reaches the olfactory epithelium, which is thus protected from potential damage caused by heat, cold and dryness (Negus, 1958 cited by Tagaki, 1989). It must be said however, that these precautions are mainly for the benefit of the delicate lining of the lungs. In humans, there is no sharp transition between olfactory and respiratory epithelium, in contrast to other vertebrates (Morrison & Costanzo, 1990). The olfactory mucosa includes the epithelium, containing the olfactory receptor cells, sustenacular cells, and basal cells and its underlying lamina propria composed of Schwann cells, blood vessels and olfactory axon bundles (Takagi, 1989).

The primary task of the olfactory mucosa is to detect odour molecules and to further encode and transmit this information to higher centres of the system. Thus, Getchell and Mellert (1991) postulate that proteins within the cells that synthesize olfactory mucus, such as Bowman's glands, must have significance for olfactory reception as they provide the microenvironment for transduction. As yet further research is needed to confirm this but it seems highly likely that such perireceptor events are central to the transduction processes (Getchell & Mellert, 1991). Perireceptor events describe an odorant's entry into, and passage through, the mucus covering the olfactory epithelium (Vogt, Rybcznski & Lerner, 1989). Such events obviously have the potential to influence the activation of receptor cells and their adaptation by promoting odorant access to or clearance from the sites of reception (Ache, 1991).

"While the detailed role of stimulus binding/degrading proteins in the perireceptor environment is as yet unclear, the presence of what appear to be functionally similar molecules in mammals as phylogenetically divergent as insects and mammals suggests that perireceptor events play an important and fundamental role in chemical signal detection. If so, it would be important that perireceptor biochemistry be studied and interpreted in conjunction with the processes of receptor cell activation, with which they presumably co-evolved" (Ache, 1991: 10) .

The importance of these perireceptor events, for coding, especially odorant binding proteins (OBP's) and degradative enzymes, such as cAMP are considered further on.

The olfactory receptor cells are bipolar neurons, approximately 5 μm in diameter and have a long process that extends towards the surface of the olfactory epithelium and ends as a terminal swelling on the surface, either as a dendritic knob or olfactory vesicle. Numerous olfactory cilia extend from the olfactory vesicle and from the epithelial surfaces for distances up to 30μm. This is where it is thought the interaction takes place with odour molecules, when odour molecules bind to the receptor proteins. Extending from the basal pole of the receptor cell is an unmyelinated axon that terminates in the olfactory bulb. Up to 200 of these axons collectively form mesaxons surrounded by

Schwann cell processes. These further form fascicles, that penetrate the cribiform plate of the ethmoid bone before terminating on the surface of the olfactory bulb. Collectively these bundles of axons are known as the olfactory nerve ie, the 1st cranial nerve (Greer, 1991). Olfaction alone of the senses projects ipsilaterally.

A remarkable feature of the olfactory system is that although the receptor cells are thought to be of central nervous system origin, and therefore are true neurons, they undergo continual turnover. The receptor cells are regenerated from precursor basal cells, the only known neurons that are capable of mitotic division. The implications of this for transduction and perception are as yet unclear. Farbman (1990) suggests that continued mitosis is under genetic control, but the length of cell life is modulated by environmental factors.

Basal cells are approximately 6μm in length and lie at the bottom of the epithelium on the basement membrane. The exact details of the process whereby the basal cells give rise to new receptor cells is not known at this time (Takagi, 1989). Sustenacular cells do not posses axons and have irregular, columnar, slender bodies characterised by bushy microvilli. Their functions include: isolation of receptor neurons from one another; glial type function; mucus secretion; and transepithelial transport of molecules; guides for migration of postmitotically active cell bodies and dendrites through the epithelium (Takagi, 1989). For the purposes of this section however they are not thought to mediate any sensory information (Greer, 1991) and so will not be considered further.

Recent advances in the field of olfactory transduction have shed some light on odour reception. Vogt, Rybcznski & Lerner (1989) suggest the following general account of the biochemical events surrounding reception and transduction in the receptor cells themselves and the periphery. Odorant binding proteins and certain enzymes provide the first filtering system for the odorants. The resulting competition between the enzymes and receptor proteins represent extracellular pathways, while intercellular pathways are represented by multiple transductory processes within the receptor neuron. Odorant

binding proteins differ in their selectivity, just as above, it has been demonstrated in receptors. The responsivity of olfactory receptors can be modified in the short term by events in the perireceptor environment, i.e., neuromodulators and hormones and in the long term by genetic means. Thus, it appears that the primary receptor cells do have a dynamic role in odour perception. The character, intensity and quality of an odorant is represented by the activity in populations of neurons, across the mucosa, whose individual sensitivity and response spectra are different.

In detail, it would seem that olfactory neurons have specialised receptor membranes, which contain a high density of proteins. Research in vision suggests that the proteins may act as a receptor. The light we see is absorbed by a protein, this activates an enzyme system through a G-protein, and this changes the internal concentration of a "secondary messenger" molecule, cyclic AMP (cAMP). It is postulated that this molecule allows the ions to flow, changing the membrane potential (Dodd, 1988). Similar events are thought to occur in olfaction and recently Buck & Axel (1991) discovered a family of genes that seem to code for receptor proteins. This gene family appears to be large, raising the possibility that much of the discrimination of odours could be accomplished at receptor level.

Structure and function in olfaction - the olfactory bulb

This section is not designed to give an exhaustive account of the synaptic organisation and functional properties of the olfactory bulb, as many excellent reviews exist already (Shepherd, 1981). Only that information which sheds light on the role of the bulb in the coding of olfactory stimuli will be discussed, following a brief structural / functional overview.

Much is known about the bulb because early investigators were keen to learn about the principles of nervous system organisation and it provided an easily accessible, and distinctly arranged structure. The olfactory bulb is remarkably consistent in its morphology across phyla. It is generally spherical, and has a concentric structure

composed of six layers: the olfactory nerve layer (superficial); the glomerular level; the external plexiform layer; the mitral cell layer; the granule cell layer; and the anterior olfactory nucleus (deepest layer). Distributed amongst the layers are five primary neurons; mitral cells; tufted cells; peri- or juxtaglomerular cells; granule cells; and short axon cells.

The most evident feature of the bulb is that it imposes a severe condensation on the number of channels of information it receives when compared to the number of channels it projects to the pyriform cortex. In terms of the information progressing up through the olfactory system, this would seem highly significant, because while there exists evidence to suggest that the activity taking place in the olfactory epithelium, in response to an odorant, might provide a sufficient basis for odour quality discrimination, is seems in the light of the above that the bulb plays a more significant role in discriminatory processing.

Mitral cells in the bulb form a distinct shell-like layer. The dendrites of mitral cells are classified into primary and secondary dendrites. The apical (primary) dendrites are directed towards the glomeruli, while the axons leave the cell body from the opposite side. The basal dendrites (secondary) run tangentially in the external plexiform layer to the granule layer. Mitral cells can also be classified as differing in the distribution of these secondary dendrites (Halasz, 1989). Tufted cells are scattered throughout the external plexiform layer, and three types have been identified according to the position of the cell body: internal; middle; and external tufted cells (Tagaki, 1989). It has become clear recently that mitral and tufted cells may be representatives of at least two parallel circuits for processing odour information (Greer, 1991).

Periglomerular neurons are found surrounding individual glomerulus but the dendrites of these neurons do not innervate the external plexiform layer. Granule cells are small, have no axons and are found in the deepest layer of the olfactory bulb. They appear in tightly packed stacks, arranged parallel with the layer and are studded with "spines." The entire synaptic output is inhibitory through these spines to the mitral cells and tufted cells, and forms an extremely powerful, targeted system of inhibition. Relatively little is known of

the short axon cells that appear in the granule cell layer and the external plexiform layer (Tagaki, 1989).

The internal synaptic organisation and neurotransmitter localisation in the bulb is of importance because of the significant role it plays in the processing of olfactory information. Unfortunately relatively little is known in this area and much further research is necessary. What is known however is that odorants activate certain populations of olfactory receptor cells which send the signal to the primary dendrites of possible topographically defined bulbar output neurons (mitral and tufted cells) in the glomeruli (Halasz, 1989). The second component of intraglomerula processing involves mitral and tufted cell reciprocal dendodendritic synapses with periglomerular cells which completes the first stage in the maintenance and amplification of specificity of an odorant signal in the olfactory bulb (Greer, 1991).

An important element in providing the vertical and horizontal interconnection within the bulb is the granule cell, which receives reciprocal dendrodendritic synapses from mitral and tufted cells. These are the most extensively studied connections of the external plexiform layer. Mitral cell axons and tufted cell axons leave the bulb in the olfactory tract.

Feedback loops project to the olfactory bulb via centrifugal axons and axonal collaterals. All appear to terminate on the basal dendrites of granule cells. Axonal collaterals arise from the anterior olfactory nucleus and terminate in the external plexiform layer. The centrifugal axons arise from the nucleus raphe, locus coeruleus, contra- and ipsilateral anterior olfactory nucleus, the pyriform cortex and are thought to modulate the activity of the bulb via excitatory synapses. They terminate at all levels in the bulb.

Structure in secondary olfactory connections

The details for this section can be found in the main body of the report, Chapter 1, integrated with details of the coding taking place at this level.

Appendix 2-Odour information

A general guide to perfumes and their nomenclature

Perfumes are very complex mixtures and have distinct stages which they pass through after they are applied to the skin. The first impression given by a perfume is called the top note, these are the lighter notes, the most volatile chemicals. Many people buy a fragrance on the basis of the top notes, only to find that they do not like the perfume after a few hours, because of the way the fragrance develops over time and changes character. The odours that next become obvious are the middle notes, a little heavier, also called the bouquet or heart notes which unfold a few moments after perfume application. Then come the base notes, the main odours of the fragrance that remain perceptible for hours rather than minutes. This is where the musks that have been added come in, to "fix" the perfume ingredients and round the whole thing off.

A further classification are the fragrance families, a set of descriptive terms used by perfumers. The following is taken from the Harman and Reihmer (H & R, 1985).

Green Notes describe the fragrance concept of leaves, wheat, grass etc. Sub-classification includes *Fresh* : light, cool notes such as lemon and green herbs. *Balsamic*: soft, warm notes from natural products.

Floral Notes form the largest fragrance reservoir in the perfume world. Not specific flowers but a "flowery" composition. Sub-classification: *Fruity-fresh* : fragrance nuances from fruits such as apple, raspberry etc. *Floral-fresh* : blossom fragrances with spring-like floweriness such as hyacinth or freesia. *Floral* : precious blossom combinations of jasmin, rose and other summery flower fragrances. *Floral-sweet* : heavy blossom directions, such as tuberose or carnation with a sweet roundness for which vanilla and musk are most characteristic.

Aldehydic Notes have an especially pronounced strength of radiation which cannot easily be compared to nature's fragrances. Sub-classification *Floral-aldehydic notes* these are often perfumer created varied blossom notes. *Aldehydic-floral-woody-powdery*

these are aldehydic floral fragrances with a woody background a "powdery" foundation of cedar, moss and soft sweetness.

Chypre Notes are unmistakable because of their bergamot accented freshness and foundation of oakmoss. Sub-classification: *Fresh-mossy- aldehydic* : fresh, aldehydic Chypre notes which are deepened through dry, algae and woody-'mossy' accents. *Floral-mossy-animalic* : these are very complex fragrance creations in which flowery, spicy, leathery and animalic fragrances are combined in a classic accord. *Mossy-fruity* : this is a heavy scent rounded off with sweet fruity nuances.

Oriental Notes have a pronounced heavy sweetness which is achieved with different resins from plants as well as animalic fragrance materials.

Tobacco / Leather Notes both of these families are essentially based on fantasy accords with birch-tar and animalic elements which are chiefly applied in the male fragrance area.

Fougere Notes have a herbaceous-fresh middle notes characterized by lavender, with moss components and coumarin in the background. In fact the Fougere fern which lent its name to the category does not have a fragrance of its own.

Table 2.2.1 A list of descriptors for each of the odours used in this thesis

Below is a list of odour descriptors for each of the odours used in this study.

Pink Quartz	Light, floral
Red Ruby	Heavy, floral
Imperial Jade	Woody, herbal
Green Emerald	Chypre
Purple Amethyst	Sweet, oriental
Yellow Topaz	Musk, floriental
Golden Amber	Spicy, oriental
Blue Diamond	Aldehydic, floral
IVA	"Sweaty feet"
Traseolide	Musky, sweet
Linalyl Acetate	Lavender, bergamot
9116	Floral, aldehydic
9178	Aldehydic, floral, sweet
9105	Sweet
9152	Sweet, floral, musky, floral
9135	Sweet, spicy, herby, woody

Thumb-nail sketches of all of the odour used in this thesis including their psychometric ratings

This section contains a thumb-nail sketch of all the odorants used in this thesis and their psychometric ratings. Numbers in brackets indicate position in the rating list. The nearer to 10, the nearer the bottom of the list, i.e., weak, unpleasant, and unfamiliar. The nearer to 1, the nearer the top of the list , i.e., strong, pleasant and familiar.

Pink Quartz - a light floral

Males and females together rated this the most pleasant of all the odours presented in the first part of the experiment but it was neither rated as very familiar (fifth on the list), nor very strong (9th). It was more familiar to women (3rd) than to men (6th) and also more familiar to left handers. Pleasantness and familiarity were strongly correlated.

In part two, its strength and familiarity ratings stayed approximately the same but it fell from top favourite to sixth. The reason for this shift was the male subjects. Pink Quartz remained top of the list for pleasantness for females, but it was last for the males, pushed out of place by the other odorants.

Red Ruby - heavy, floral.

This odour was rated by both sexes as fairly strong (5th) but not at all pleasant (9th) or familiar (10th). The strength and familiarity were very strongly correlated. Males and females did not differ by much on their ratings for this odour, either in the first or the second parts of this test.

Golden Amber- spicy, oriental.

This odour was perceived as being very strong for males and females in the first part of the test (2nd) and very familiar (3rd) but not particularly pleasant (5th). Golden Amber is significantly more familiar to menstruating women.

Part two revealed that the perception of Golden Amber hadn't altered much, it was still (10th) for males and females for pleasantness, but this difference was significant. The rating for pleasantness by males was higher than that given by females. The positioning for familiarity for males (10th) and females (3rd) was not significant.

Blue Diamond 20% - Aldehydic, floral.

Blue Diamond was perceived by both sexes as strong (3rd), pleasant (4th) and the most familiar odour. Although the differences are not significant, it was rated higher for strength by females than by males (2nd as opposed to 7th) but as more pleasant and familiar by the males than by the females. (2nd and 5th in both cases). The correlation between the dimensions pleasant/ familiar was very strong and strong between strength and familiarity.

Part two of the test revealed again no significant differences on any of the dimensions, although its familiarity rating had slipped to third and both males and females rated it as less pleasant the second time around, males 2nd down to 5th, females 5th down to ninth.

Blue Diamond 1%

This odour was rated as the weakest and the most unfamiliar by both males and females, but the males found it significantly more pleasant than the females. There was a correlation between pleasantness and strength.

Blue Diamond 0.25%

This odour was perceived as blank by all but two of the subjects and so was excluded from the analysis. Even those subjects who did detect it rated it as 5 for both pleasantness and familiarity which must call into question even their judgements.

Yellow Topaz - Musk, floriental.

This fragrance was rated by both sexes together as very weak (10th) but very pleasant (2nd) and quite familiar (4th). The separation of the sexes left these positionings virtually unchanged.

Yellow Topaz was rated as significantly weaker by smokers and left handers, than by non-smokers and right handers respectively. Pleasantness and familiarity were correlated and there was a very strong correlation between strength and familiarity.

For the second part of the test if was rated almost the same for strength and pleasantness but its familiarity rating was reduced, and this was more pronounced for the males.

Purple Amethyst - Sweet, oriental

This odour was rated as strong, fairly unpleasant and rather unfamiliar by both sexes, both together and separately. There was a strong correlation between pleasantness and familiarity, in this case Purple Amethyst was relatively unpleasant and unfamiliar. Purple Amethyst was found significantly less familiar by menstruating women than by non-menstruating women and men.

Green Emerald- Chypre

This odour was rated as strong (4th) for both males and females combined, pleasant (3rd) and relatively unfamiliar (7th). Ratings by the sexes did not differ by much, two positions on the list at the most. There was a strong correlation on the dimensions of pleasantness and familiarity, and a very strong correlation between strength and familiarity. Green Emerald was rated as being significantly weaker by left handers compared to right handers.

Imperial Jade- Woody, herbal.

Imperial Jade was rated very similarly by both sexes, being found fairly strong, very unpleasant (slightly more so by males) and very unfamiliar. There were strong correlations between pleasantness and familiarity and strength and familiarity.

Traseolide - Sweet, musk.

Again this odour was rated similarly by the sexes both combined and separate. It was rated the weakest odour, the most unfamiliar but fairly pleasant (6th). There were very strong correlations between each of the three dimensions. A significant finding was that it was less familiar to right handers than to left handers.

Iso-Valeric Acid - "sweaty feet"

This is a very strong, unpleasant odour and was rated by both sexes as being the strongest and most unpleasant odour. There was a difference between the sexes for familiarity, males finding it much more familiar (1st) than females (6th). Could this be a reflection of the possible differing standards of hygiene of the two groups ? The correlations were as expected with a very strong negative correlation between pleasantness and strength.

Linalyl Acetate- Lavender, bergamot

When the males and females are taken together this odour is a very mid-line odour. It is rated as fairly weak (6th) fairly pleasant (7th) and fairly familiar (6th). The differences between the sexes are not significant but it was more strong for the females (4th) than the males (8th), and much more familiar for the females (1st) than the males (9th). There was a strong correlation between pleasantness and familiarity and a weaker one between strength and familiarity. Linalyl was also rated as weaker by smokers than non-smokers and weaker by left handers than right handers.

9116 - Floral, aldehydic.

Used only for the second part of the test. Virtually no differences between the ratings given by males or females. Overall it was rated as fairly strong (5th), fairly pleasant (4th) but very familiar (1st). There was a strong correlation between pleasantness and familiarity. For strength the rating was 5th.

9178 - Aldehydic, floral, sweet.

There were no correlations on any of the dimensions for this odour. It was however significantly more pleasant for males than for females. Despite their relative positioning of this odour on the familiarity scale, males (9th) and females (2) there was no significant difference.

9105 - Sweet.

Again, for this odour there were no significant differences between males and females it was found quite weak (7,9th) and quite unfamiliar (7,10th) but their respective ratings for pleasantness were males (1st), females (6th). There was also a very strong correlation between pleasantness and familiarity.

9152 - Sweet, floral, musky, fruity.

The rating for this odour was similar to the two above, no significant differences between the sexes and a strong correlation between pleasantness and familiarity. It was rated as being quite strong (4th), pleasant (7th) and quite familiar (5).

9135 - Sweet, spicy, herby, woody.

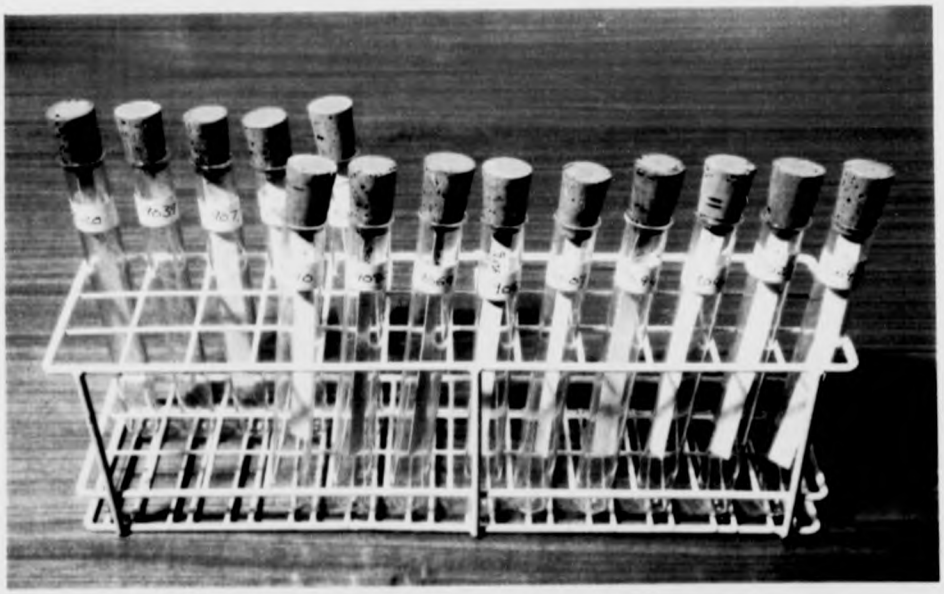
No significant differences between males and females, but their judgements of strength, males (1st) females (6th), pleasantness, males (8th), females (4th) and familiarity, males (5th) females (8th), are quite well separated by position. There was also a very strong correlation between pleasantness and strength.

PAGE(S) MISSING
NOT AVAILABLE

18, 19, 21,

Plate 2.2.1. The odours for this study ready for presentation.

Note: The odours are shown in their two groups.



Subject instruction and answer sheet for the subject olfactory evaluation test

SUBJECT ANSWER FORM FOR OLFACTORY EVALUATION TEST

NAME _____ DATE_____

INTENSITY TEST

IN FRONT OF YOU ARE FIVE JARS CONTAINING A SAMPLE OF PERFUME AT DIFFERENT STRENGTHS. PLEASE PLACE THE SAMPLES IN ORDEROF INTENSITY.

1. STRONGEST
2.
3.
4.
5. WEAKEST

TRIANGLE TESTS

EACH OF THE FOLLOWING SETS CONTAINS THREE SAMPLES, TWO OF WHICH ARE IDENTICAL AND ONE IS DIFFERENT. FOR EACH SET, CIRCLE THE NUMBER OF THE ODD SAMPLE.

1.	168	033	429
2.	315	991	205
3.	232	982	231
4.	190	188	981
5.	320	891	105
6.	955	277	718

Experimenter's answer sheet for the olfactory evaluation test

NAME: _____

ANSWERS TO MEMORY EVALUATION TEST:

1.	FEMME ROCHAS	POISON	CHANEL
2.	TUBEROSE	MUGET	JASMIN
3.	FRESH	TARRAGON	GREEN VEG.

ANSWERS TO THE IDENTIFICATION TEST:

1.

2.

3.

4.

5.

6.

7.

8.

9.

10.

Subject information form for experimental study I & II

SUBJECT INFORMATION FORM

NAME	_____
SEX	FEMALE/ MALE*
AGE	_____
ARE YOU ?	LEFT/ RIGHT HANDED
IS YOUR GENERAL HEALTH ?	Excellent/average/poor
IS YOUR DIET ?	Excellent/average/poor
DO YOU SMOKE ?	Yes/No*

IF YOU ARE FEMALE, ARE YOU MENSTRUATING TODAY ? Yes/No

IF YOU ARE NOT. WHERE ARE YOU IN YOUR CYCLE ?

_____(Weeks to menstruation)

*Delete as appropriate

YOUR COMMENTS AFTER THE EXPERIMENT (please write below)

Psychometric rating sheet used by the subjects

SUBJECT _____

PLEASE RATE EACH OF THE THREE ODORS ON THE FOLLOWING SCALES

A.

(i) unfamiliar _____ familiar

(ii) weak _____ strong

(iii) unpleasant _____ pleasant

B.

(i) weak _____ strong

(ii) unpleasant _____ pleasant

(iii) unfamiliar _____ familiar

C.

(i) unpleasant _____ pleasant

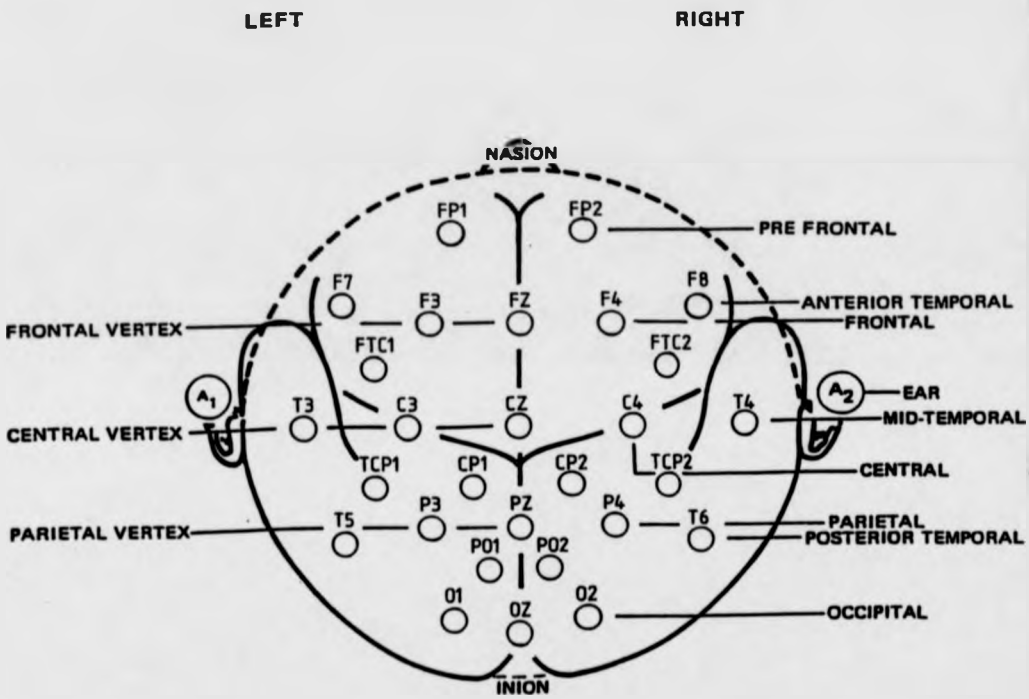
(ii) unfamiliar _____ familiar

(iii) weak _____ strong

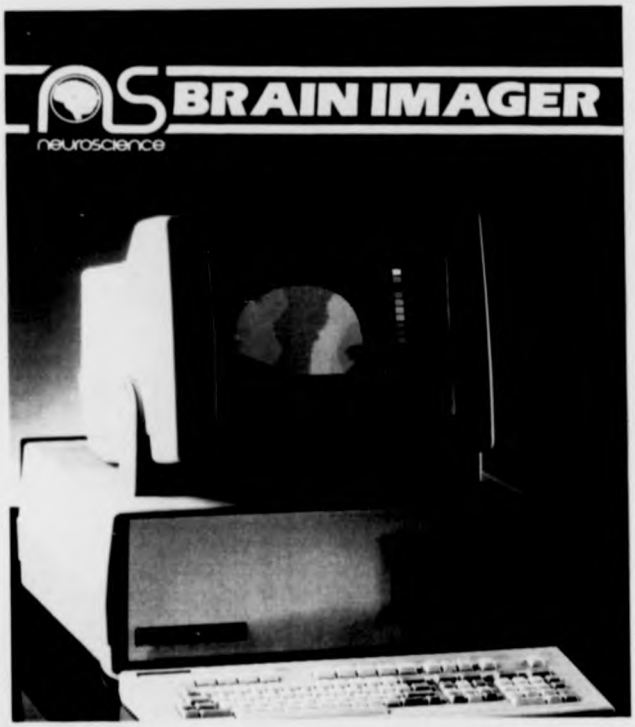
Appendix 4-Technical information

Appendix 4-Technical information

Figure 2.4.1. Electrode locations used in the present study



Plates 2.4.1 & 2.4.2. Photographs of Neuroscience Series III Brain Imager



Technical details concerning the Brain Imager and the data produced

This study used a Neuroscience Series II Brain Imager. Electrical activity from the scalp of the subject was picked up by tin electrodes located in a washable Lycra headcap (see Plate 4). The electrodes were arranged in a modification of the International 10/20 placement system (see Plate 1). When a subject was being tested electrode gel (tradename-Electrogel) was injected into the gap between the scalp and the electrode. The skin on the scalp was then slightly abraded with a blunt needle, to lower the impedance levels.

Each of the 28 data channels was amplified and then filtered by an external pre-amplifier. The data was then sent to an analogue to digital converter where the data was sampled and digitised. The sampling rate was 256 Hz. The resulting digitised data was then transformed by a dedicated chip, performing an Fast Fourier algorythm, at the rate of 100 samples per second. The FFT performed by this Imager is described by Kendal-Reed (1990):

"To perform the FFT the digitised data are divided into "bins" of 0.39Hz width. This is the fundamental or lowest resolvable frequency of the FT and is the inverse of the time period or epoch length. Hence an epoch length of 2.56 seconds gives an inverse of 0.39Hz. The maximum resolvable frequency is given by the fundamental frequency multiplied by half the number of samples in an epoch. This equals (128x0.39) a figure just short of 50Hz. The data are thus held in 128 frequency bins each 0.39 wide. Only the lowest 77 bins are further processed because of the Imagers mainly clinical application." (Kendal-Reed, 1990: 22, Vol.2)

The resulting values are used to create coloured topographical maps, based on a four point linear interpolation procedure. Thus, a map, frame or epoch (interchangeable terms) consist of 2.56 seconds of averaged power data. The data was recorded on to optical discs.

When recording was taking place the parameters were as follows: 256/512 microvolt sensitivity. Filters were set at 0.3 Hz to 40 Hz. The mains filter was turned off, the autoscaling function was on and the multi-map facility was showing on screen, so that artifact could be more readily detected.

The topographical maps can be decomposed into raw data for analysis. An example of a data frame produced by the Imager can be seen in Figure. 2. The data was downloaded from the optical to floppy discs, and a visual artifact search took place at this time. Any artifactual frames found, were deleted. The data was then transferred by a programme designed by the Psychology Department (G.Milligan) to the computer used for analysis. At this stage in the procedure frames of data could be deleted if necessary, for the particular analysis taking place. It was also possible at this stage to read the data into the statistical package being used.

Figure 2.4.2 An example frame of B.E.A.M. data

Title

Electr.	Delta	Theta	Alpha	Beta I	Beta II
	The following data are from ----------				frame 0
FP1	50	12	8	7	8
Fz	43	18	10	7	7
Cz	38	12	9	6	8
Pz	74	25	29	23	14
Oz	57	14	21	10	11
F3	33	12	9	8	8
C3	36	10	9	8	8
P3	62	25	21	19	14
O1	36	11	17	8	11
F7	78	21	15	8	12
T3	33	8	5	4	21
T5	73	21	7	12	14
FTC1	33	10	10	6	8
TCP1	50	21	10	11	0
CP1	33	12	9	9	10
PO1	27	22	47	28	11
FP2	38	10	9	6	7
F4	33	12	10	6	8
C4	38	10	9	6	10
P4	43	10	16	14	10
O2	27	10	20	11	8
F8	45	10	10	6	8
T4	29	8	5	4	16
T6	48	17	12	10	8
FTC2	3	10	6	9	8
TCP2	26	12	5	6	9
CP2	43	11	8	7	7
PO2	34	11	28	21	8

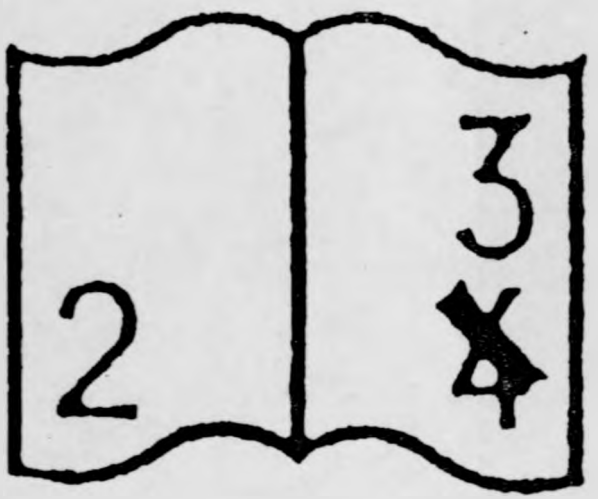
Plate 2.4.3 Photograph of a simulated presentation of an odour to a subject

Appendix 5-Analysis information

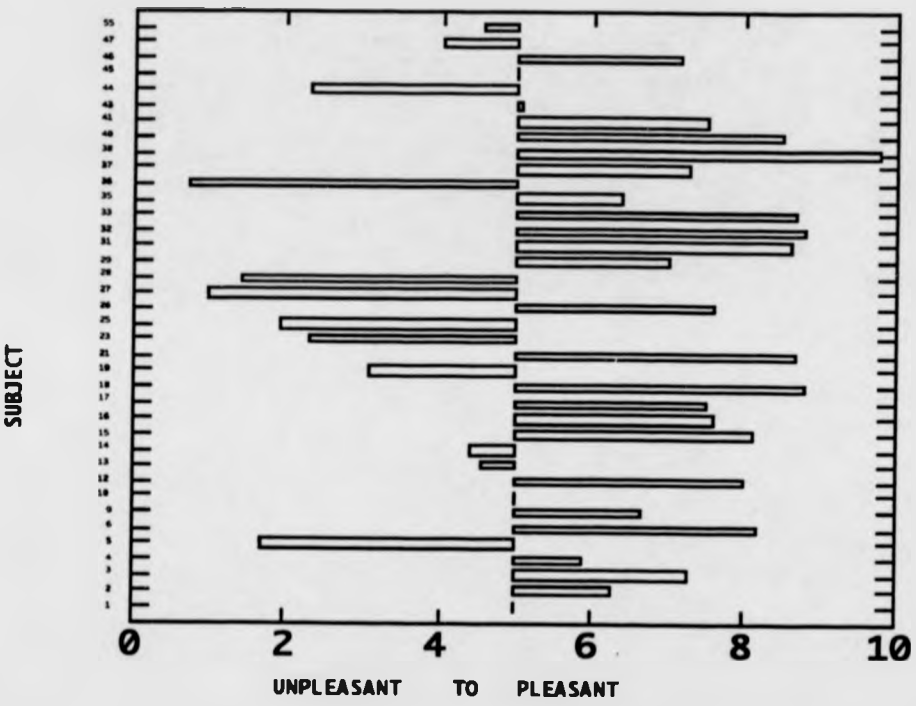
Psychometric graphs showing the rating of each subject for each dimension, for each odour

PAGINATION ERROR

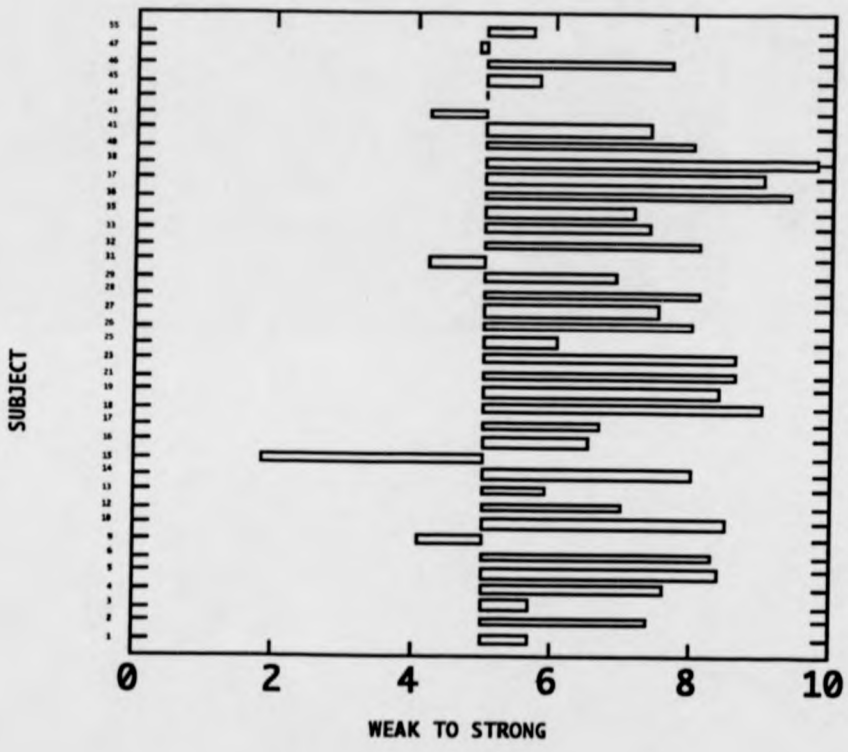
33 - 34



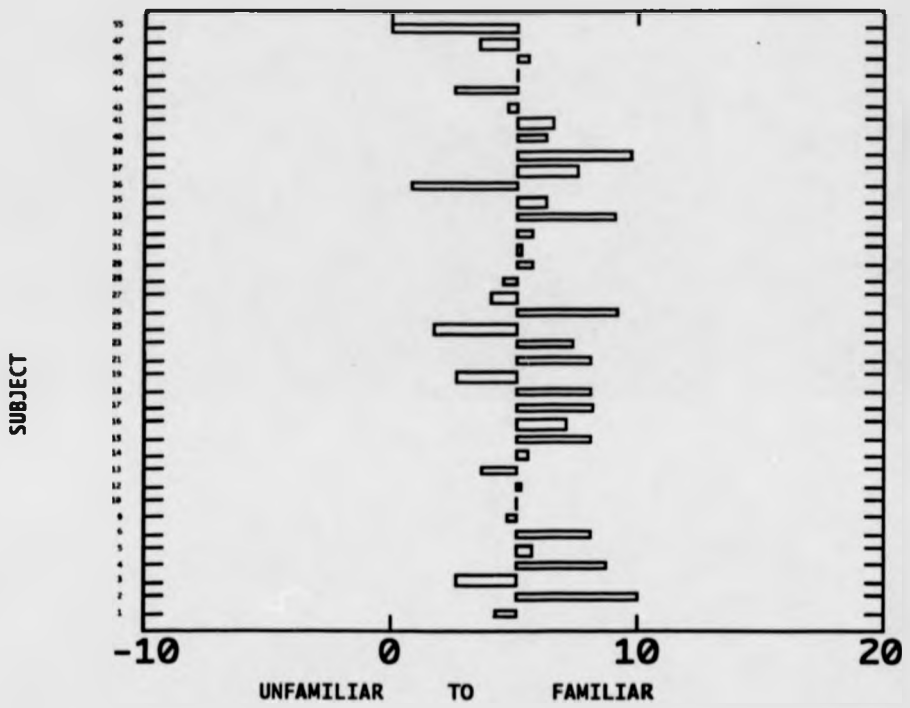
Subject ratings on the pleasant-unpleasant dimension for Purple Amethyst



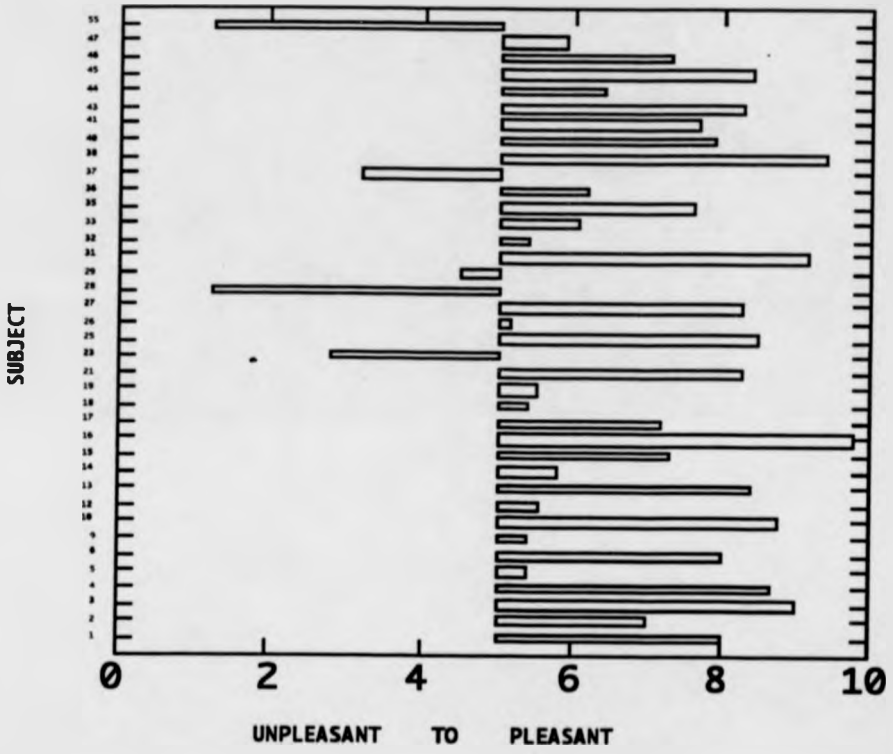
Subject ratings on the strong-weak dimension for Purple Amethyst



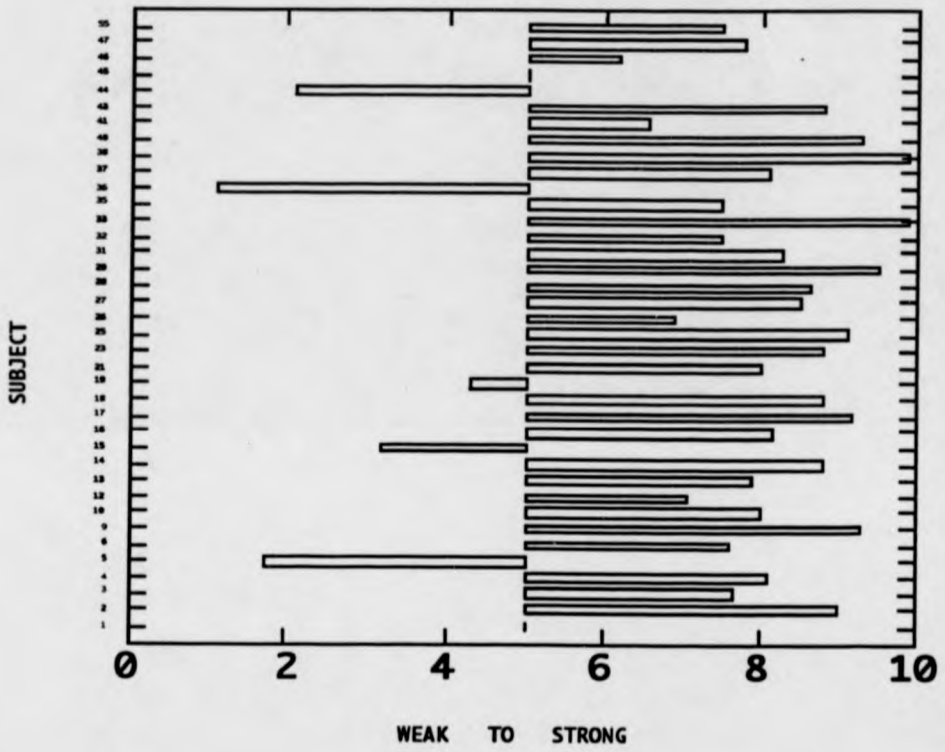
Subject ratings on the familiar-unfamiliar dimension for Purple Amethyst



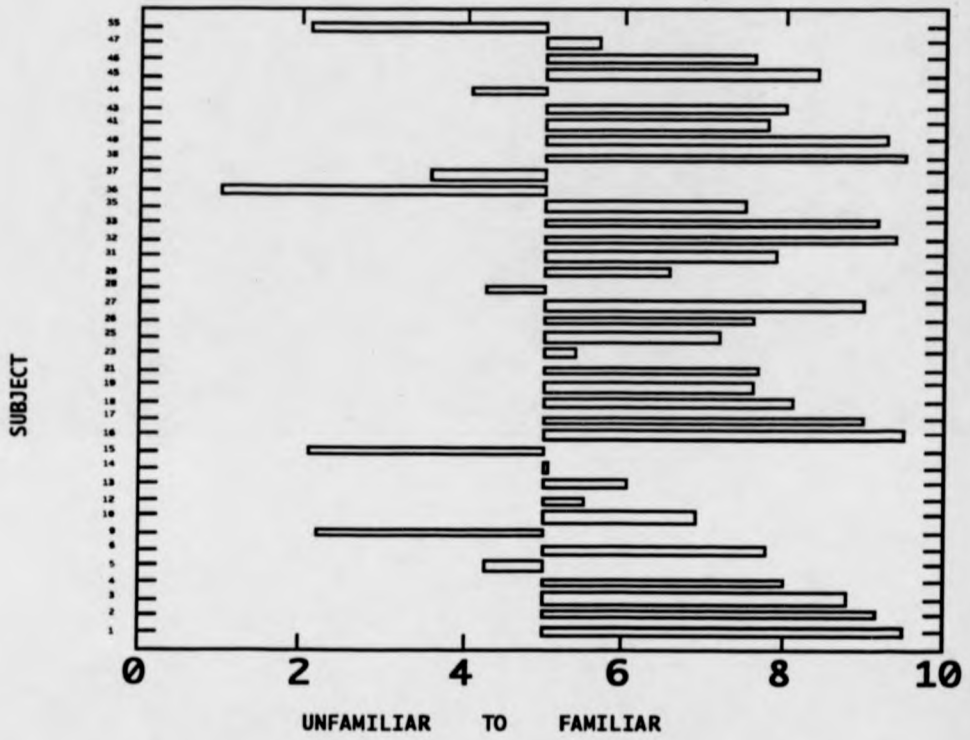
Subject ratings on the pleasant-unpleasant dimension for Blue Diamond



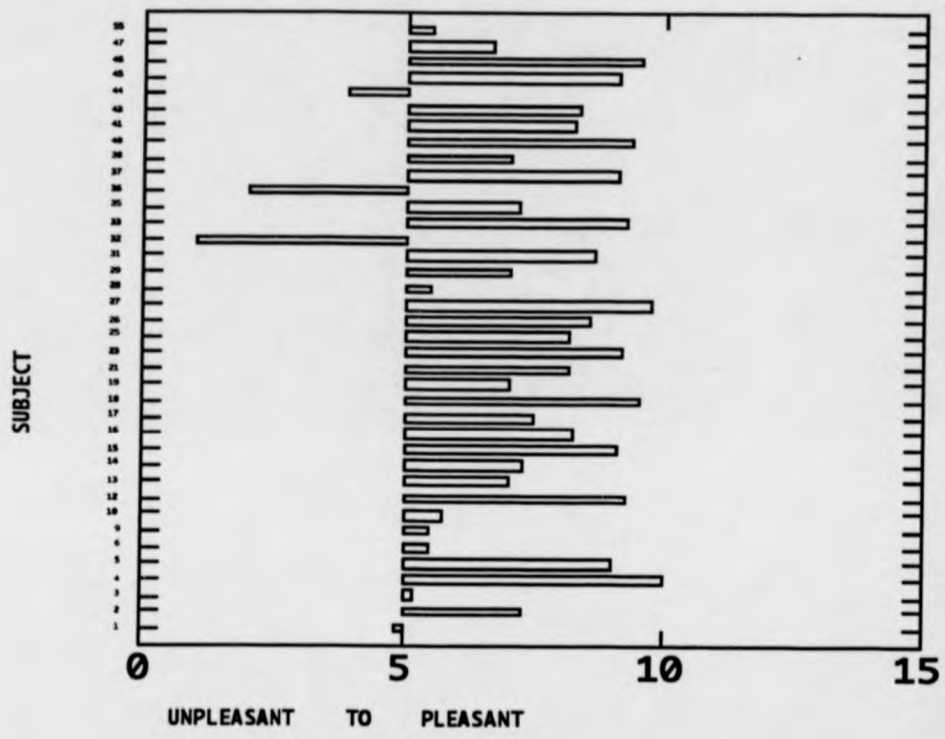
Subject ratings on the strong weak dimension for Blue Diamond



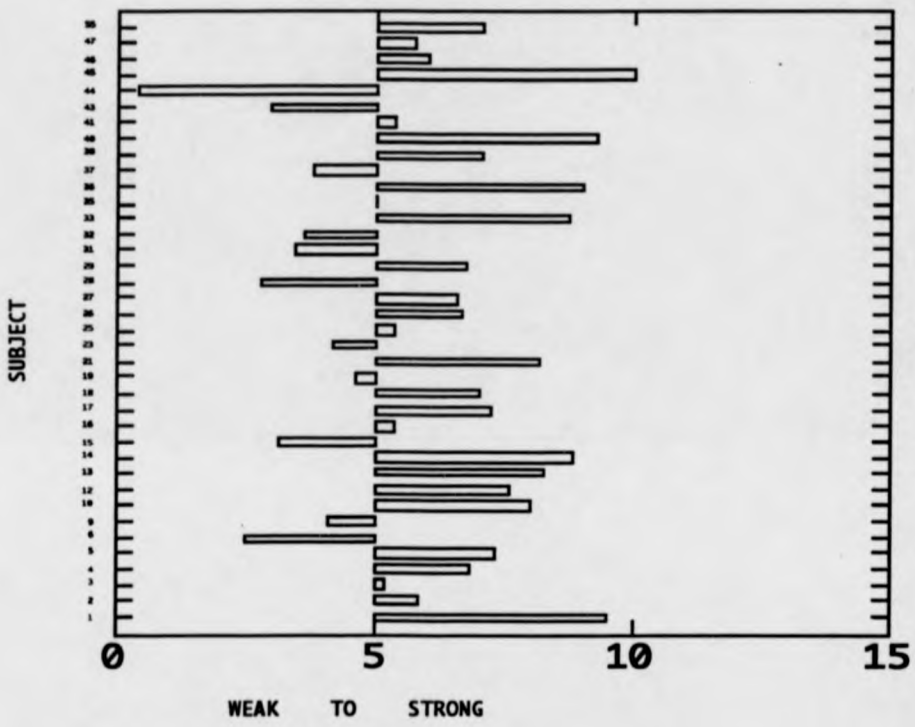
Subject ratings on the familiar-unfamiliar dimension for Blue Diamond



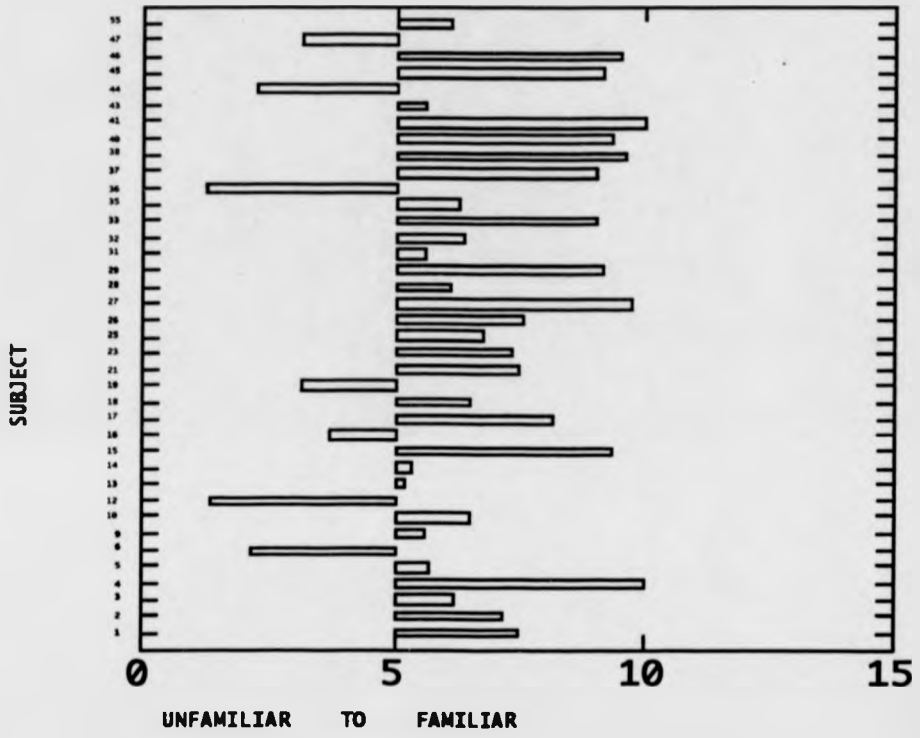
Subject ratings on the pleasant-unpleasant dimension for Pink Quartz



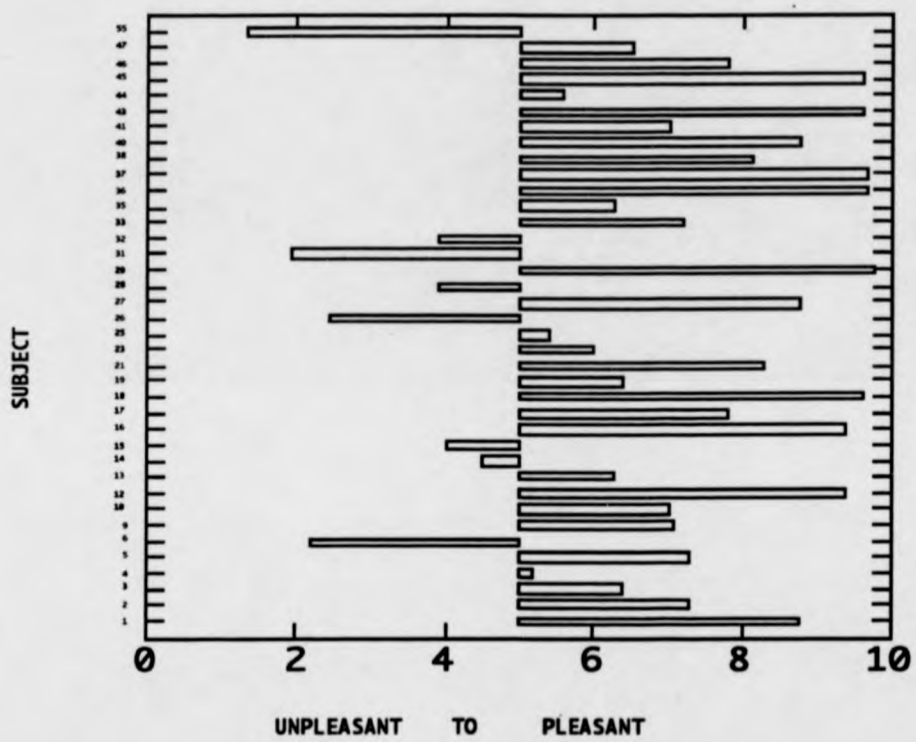
Subject ratings on the strong-weak dimension for Pink Quartz



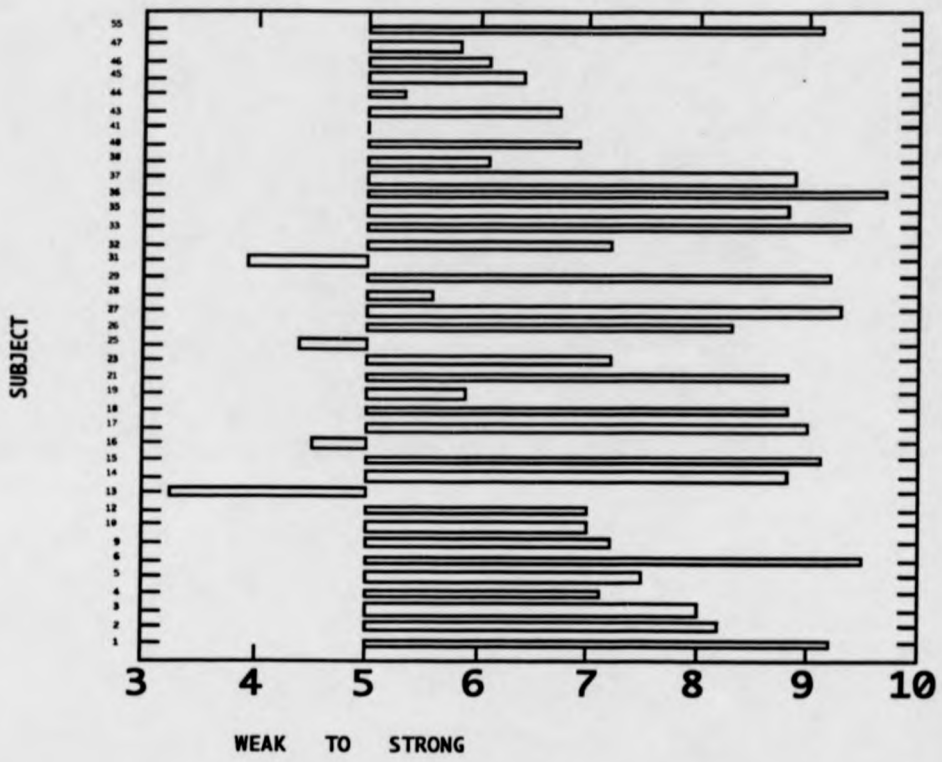
Subject ratings on the familiar-unfamiliar dimension for Pink Quartz



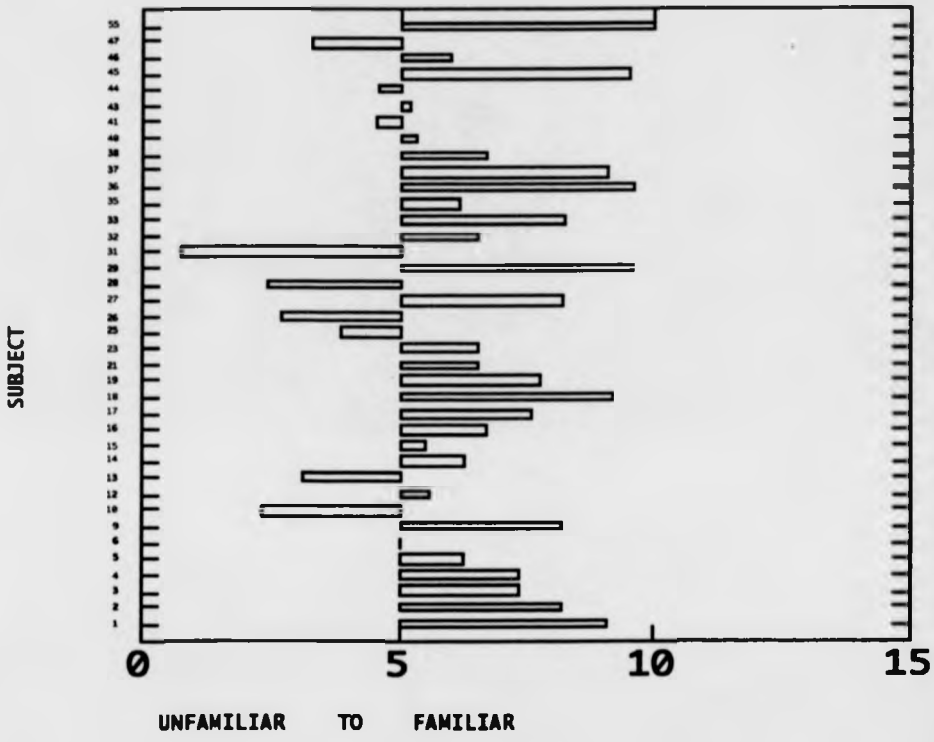
Subject ratings on the pleasant-unpleasant dimension for Green Emerald



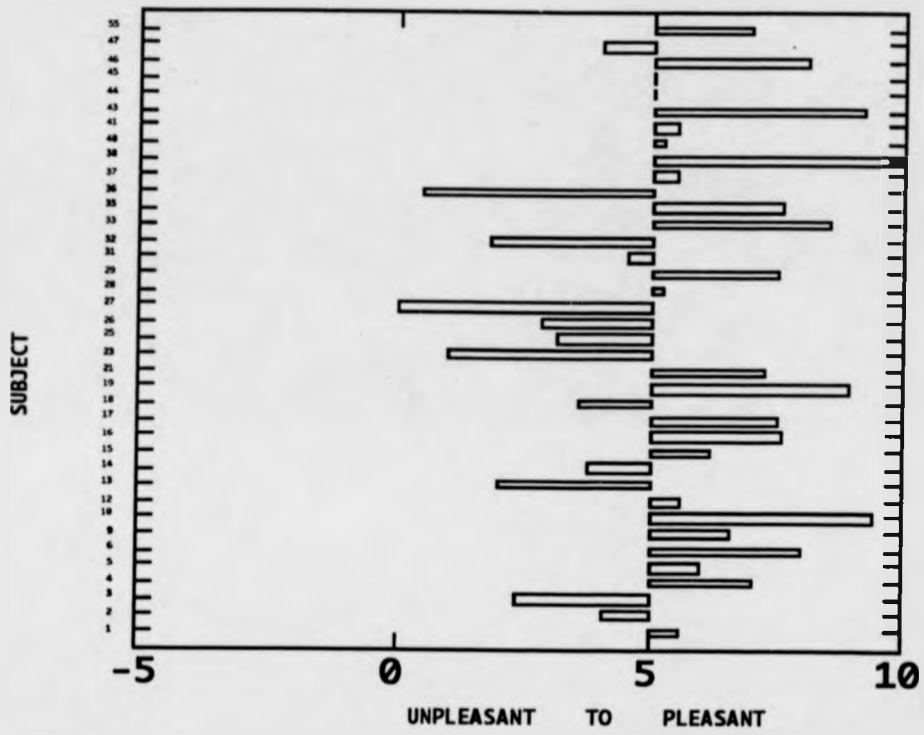
Subject ratings on the strong-weak dimension for Green Emerald



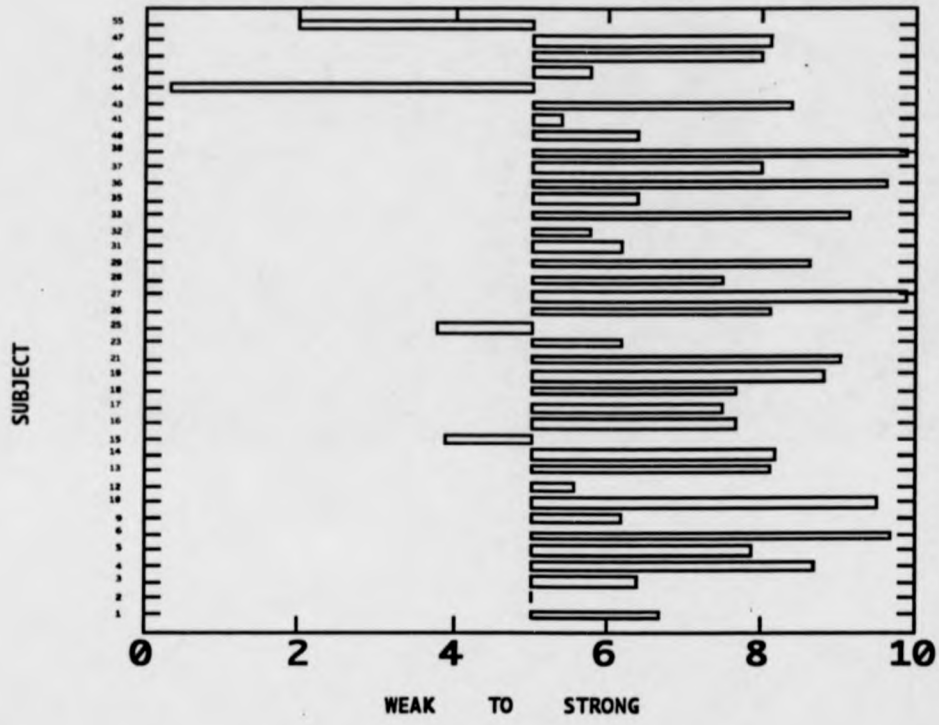
Subject ratings on the familiar-unfamiliar dimension for Green Emerald



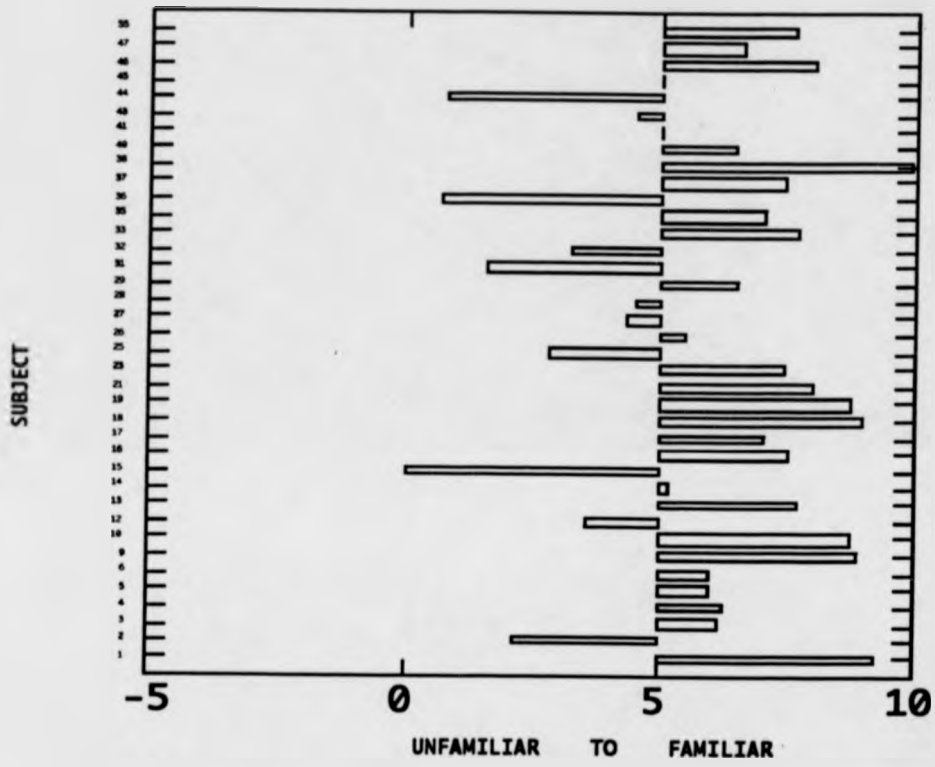
Subject ratings on the pleasant-unpleasant dimension for Imperial Jade



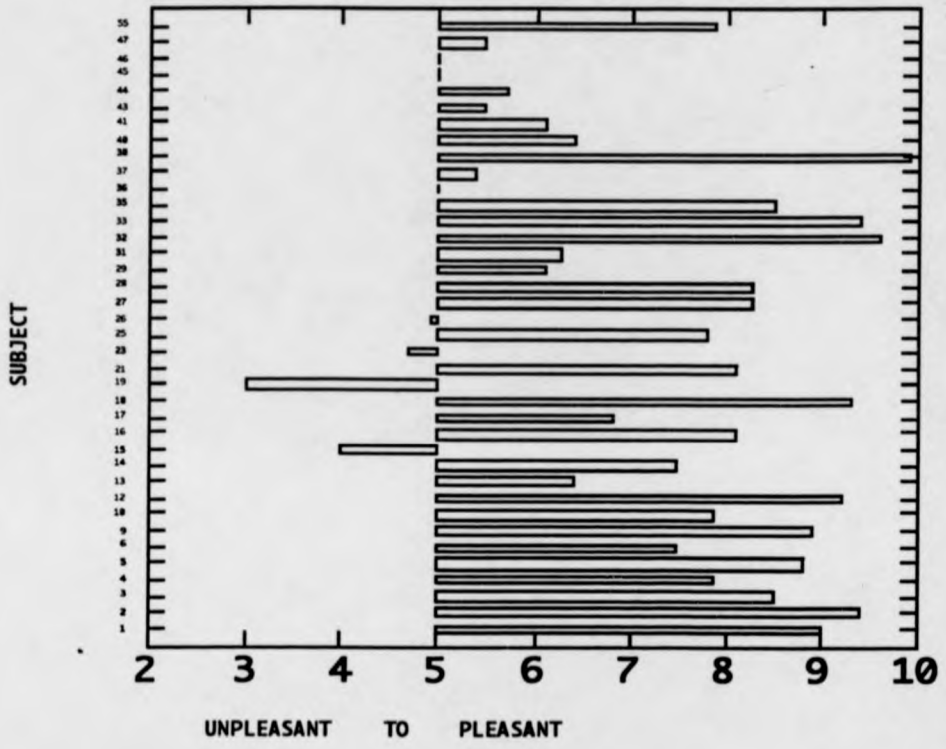
Subject ratings on the strong-weak dimension for Imperial Jade



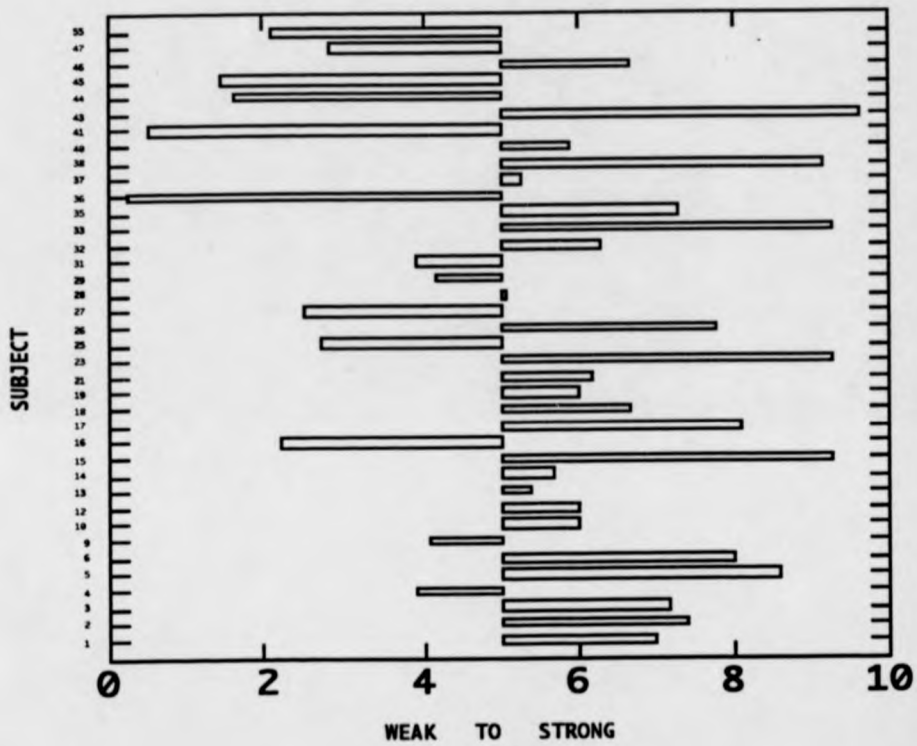
Subject ratings on the familiar-unfamiliar dimension for Imperial Jade



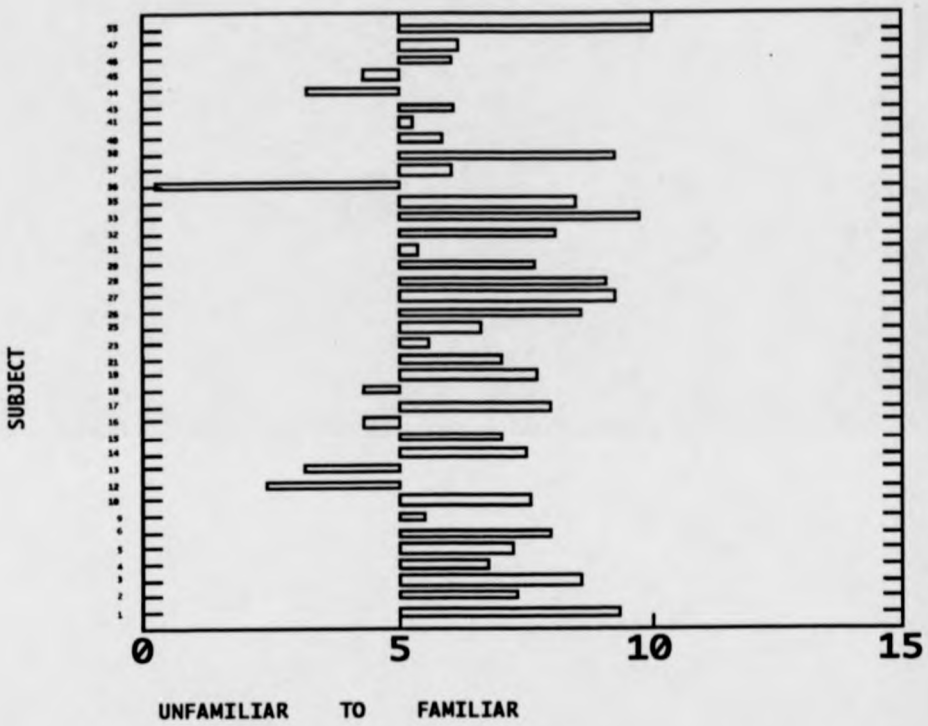
Subject ratings on the pleasant-unpleasant dimension for Yellow Topaz



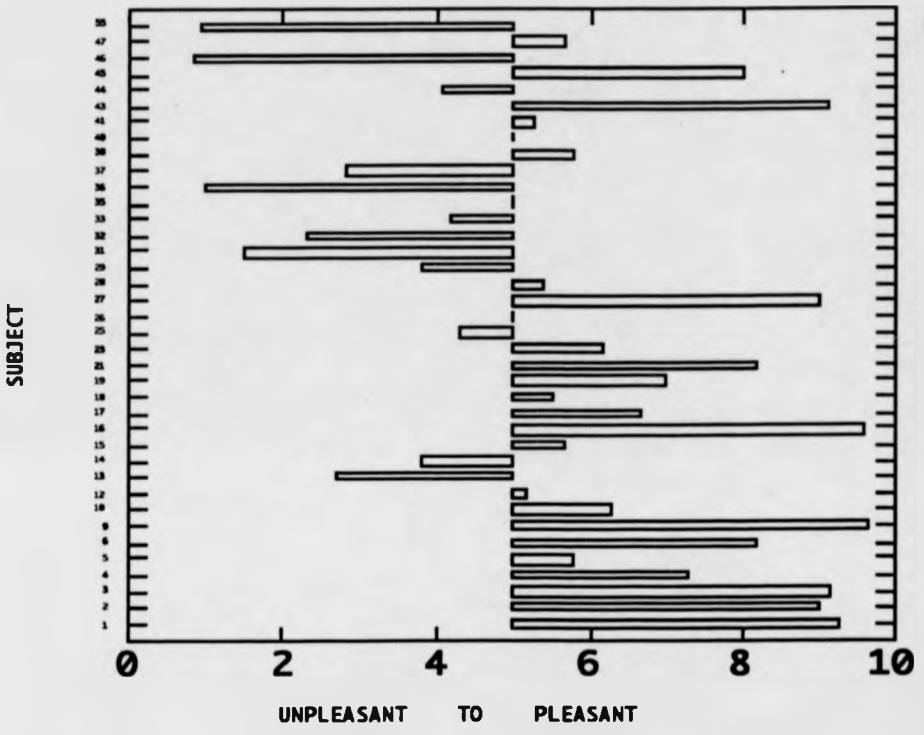
Subject ratings on the strong-weak dimension for Yellow Topaz



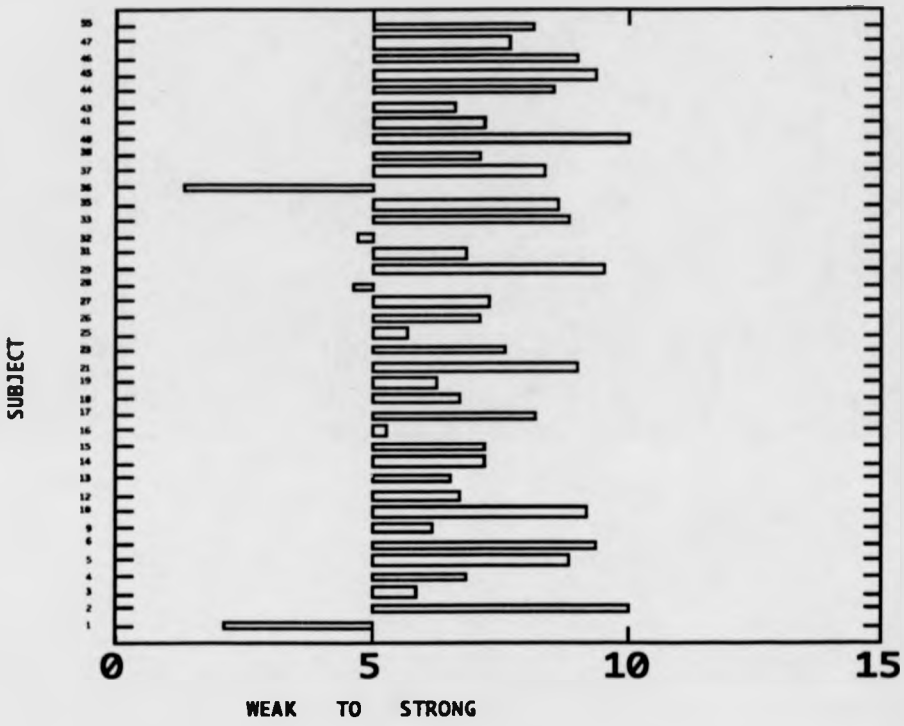
Subject ratings on the familiar-unfamiliar dimension for Yellow Topaz



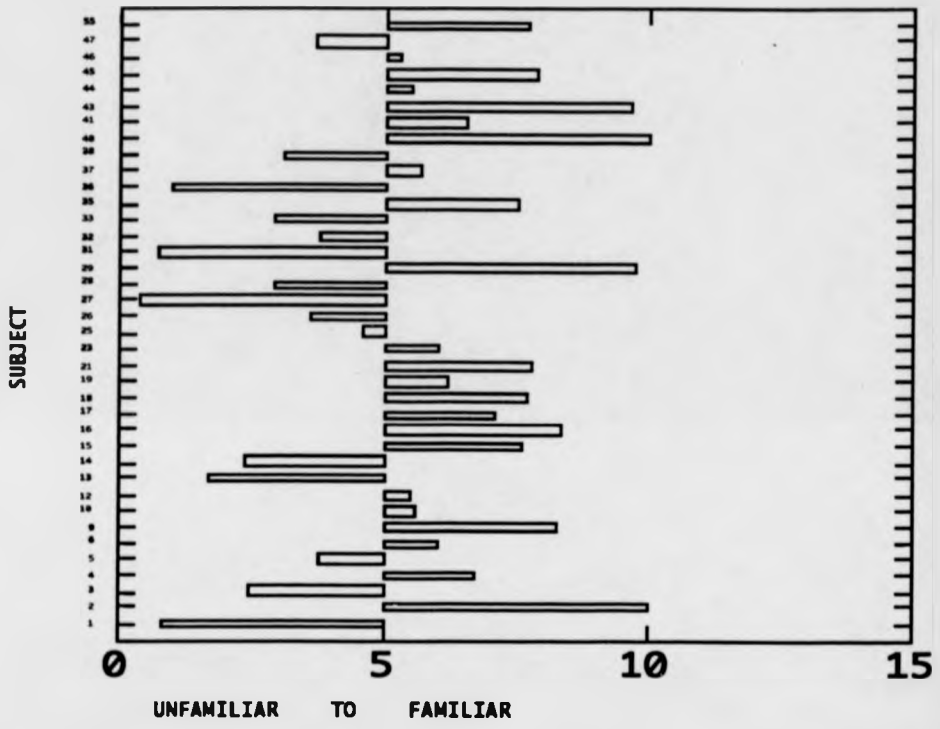
Subject ratings on the pleasant-unpleasant dimension for Red Ruby



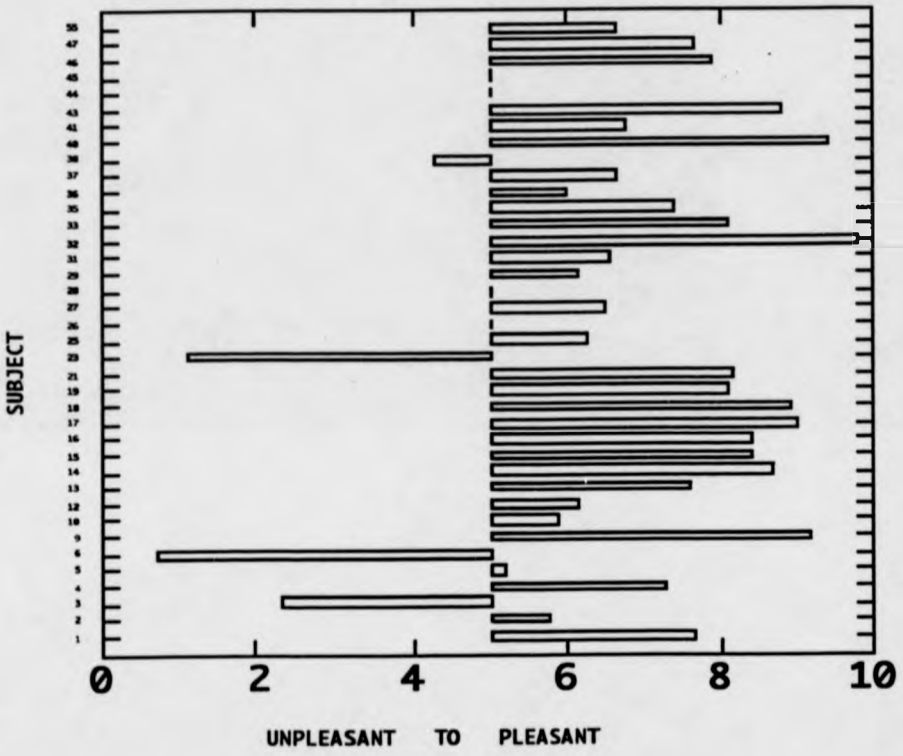
Subject ratings on the strong-weak dimension for Red Ruby



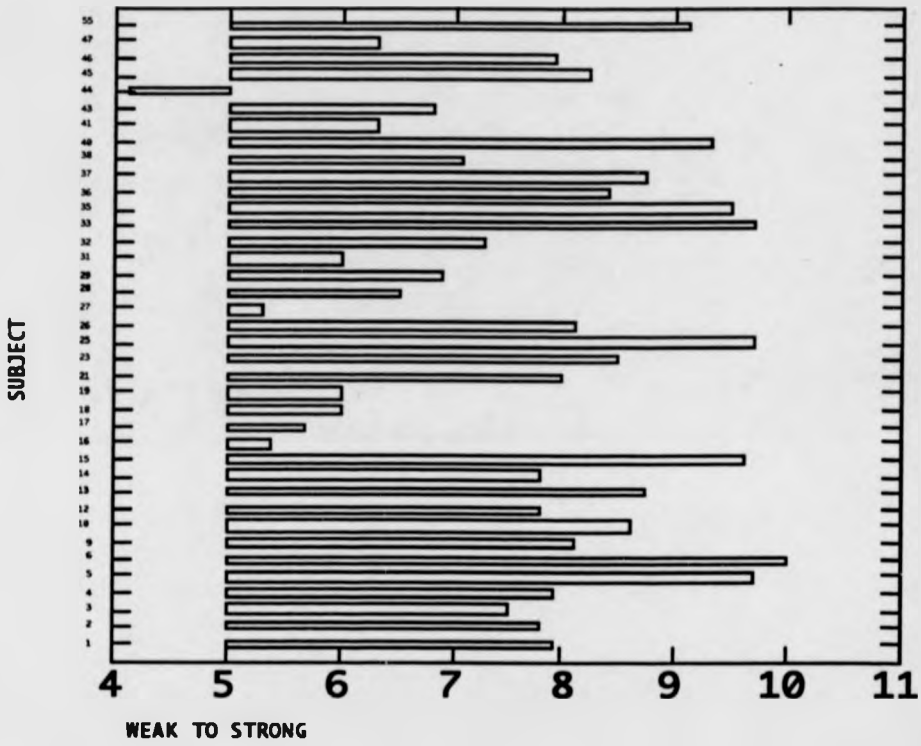
Subject ratings on the familiar-unfamiliar dimension for Red Ruby



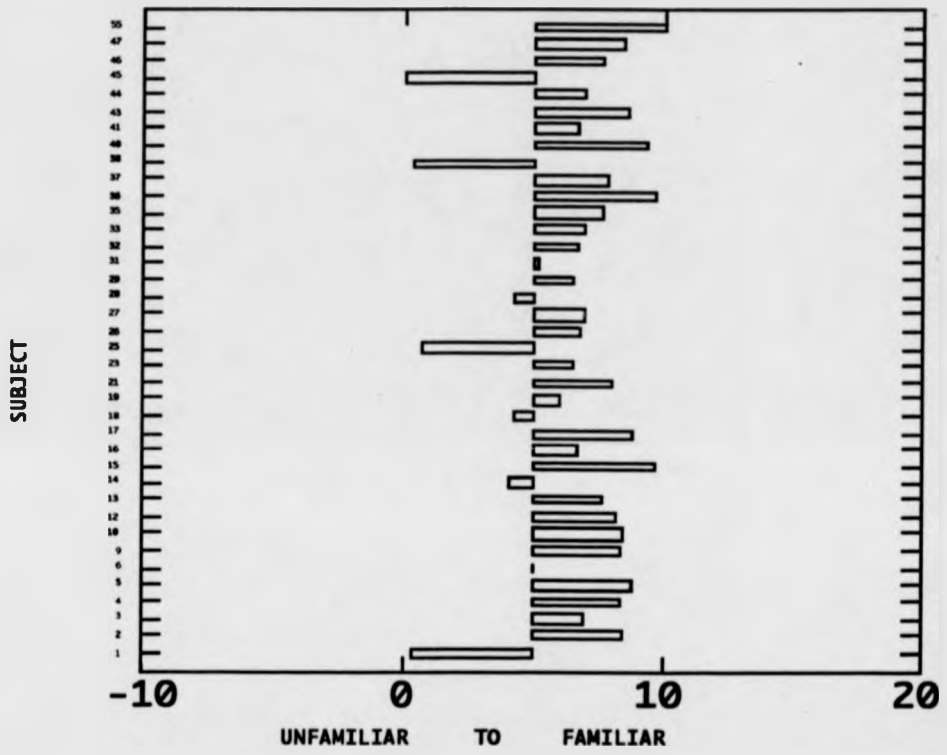
Subject ratings on the pleasant-unpleasant dimension for Golden Amber



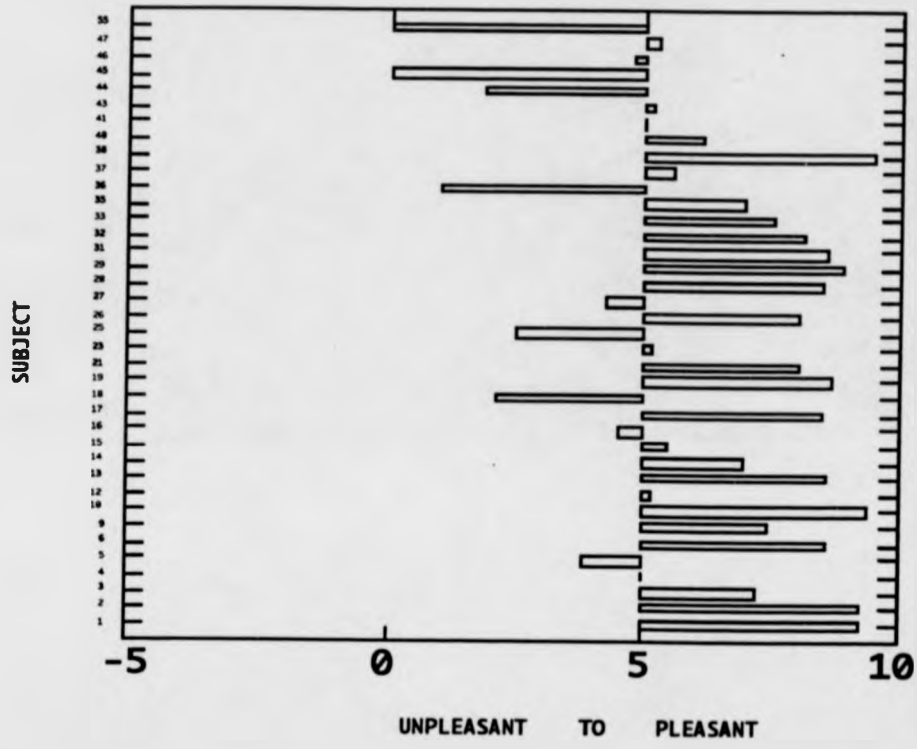
Subject ratings on the strong-weak dimension for Golden Amber



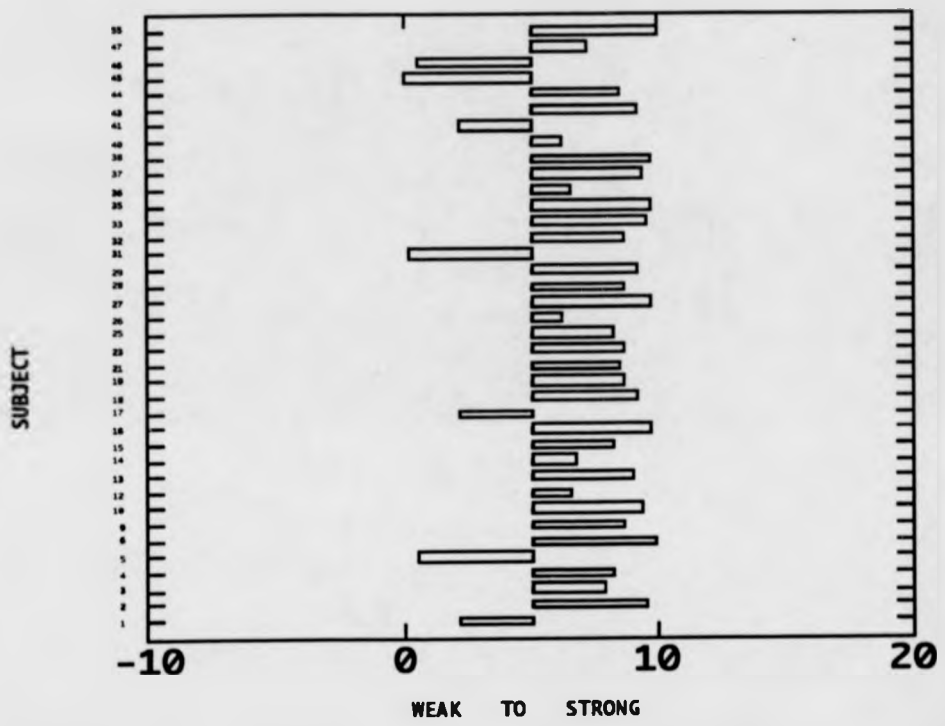
Subject ratings on the familiar-unfamiliar dimension for Golden Amber



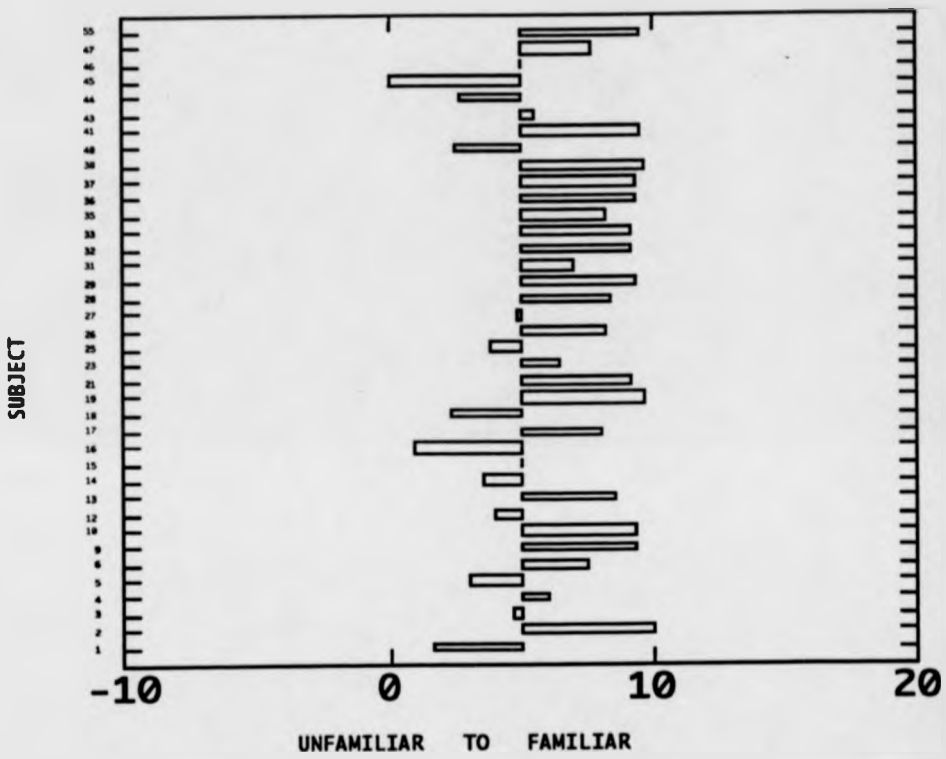
Subject ratings on the pleasant-unpleasant dimension for Linalyl Acetate



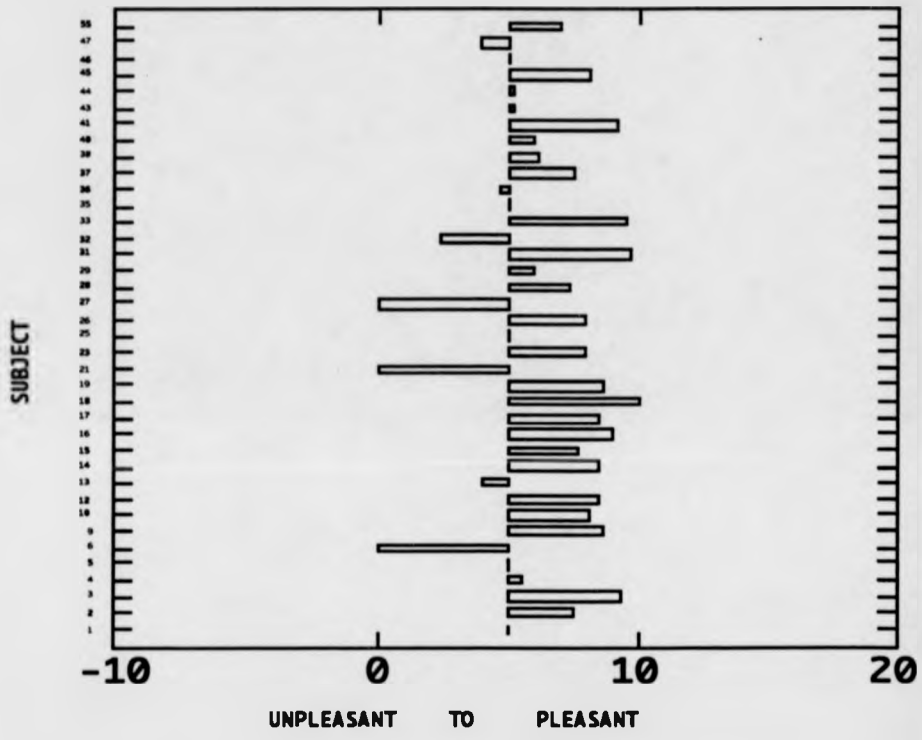
Subject ratings on the strong-weak dimension for Linalyl Acetate



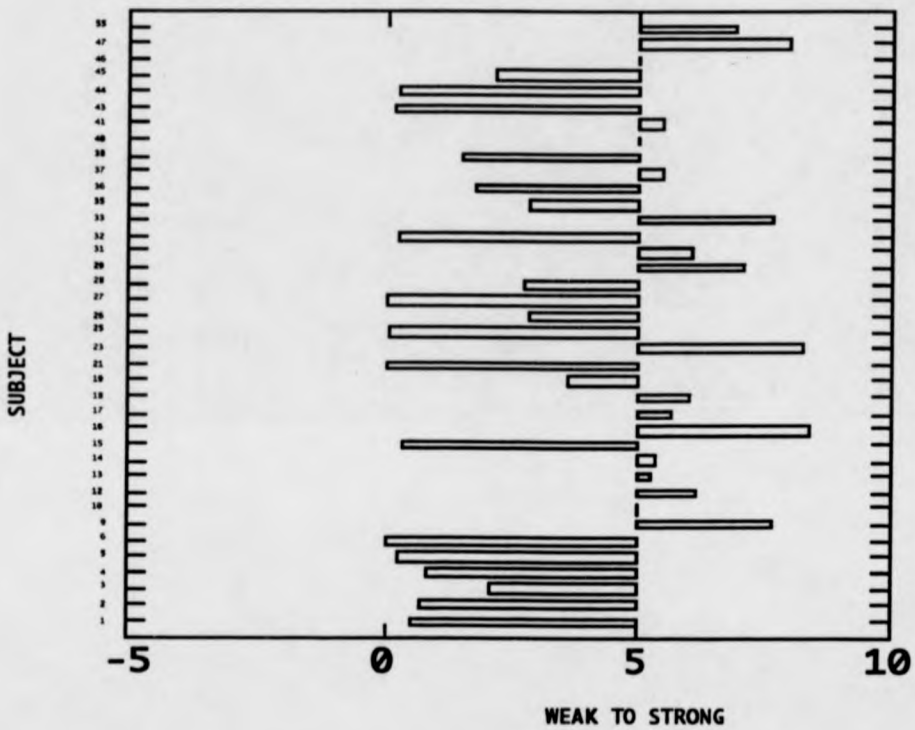
Subject ratings on the familiar-unfamiliar dimension for Linalyl Acetate



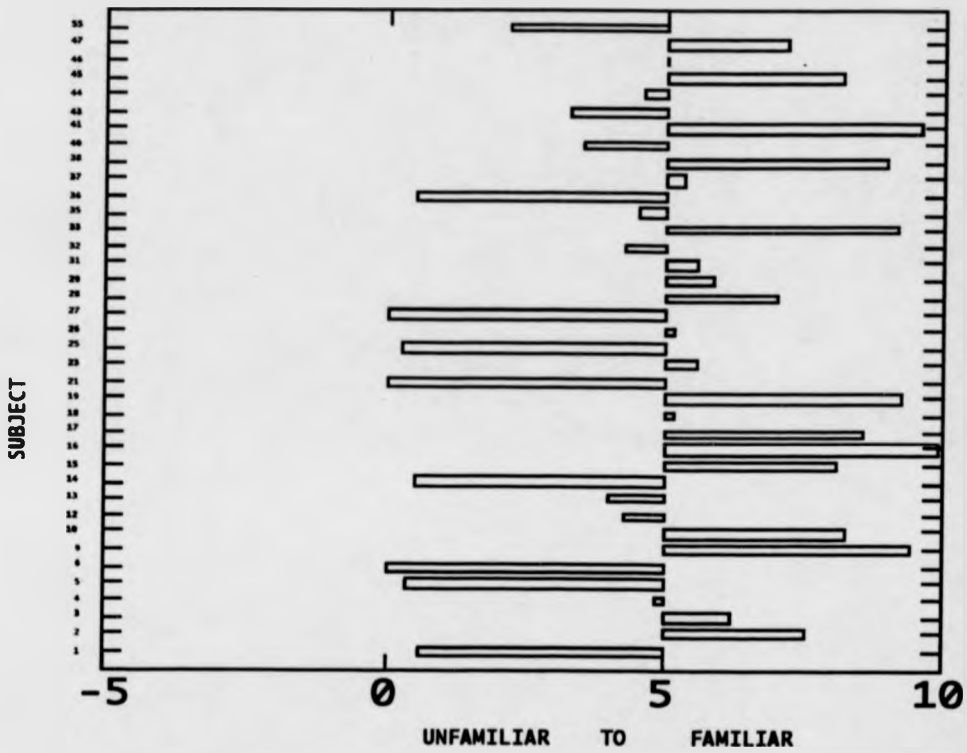
Subject ratings on the pleasant-unpleasant dimension for Traseolide



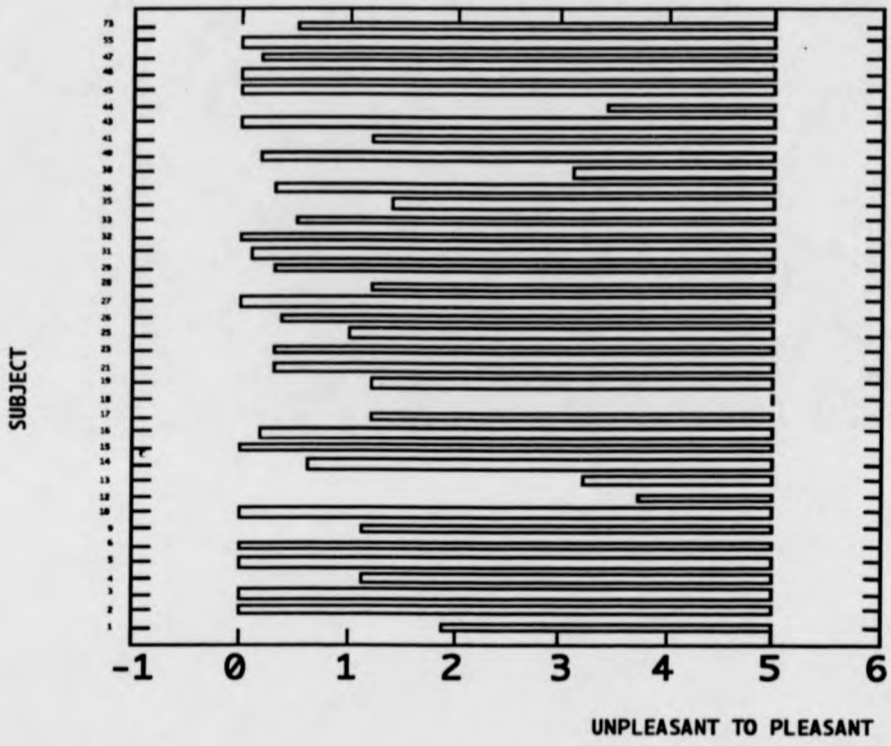
Subject ratings on the strong-weak dimension for Traseolide



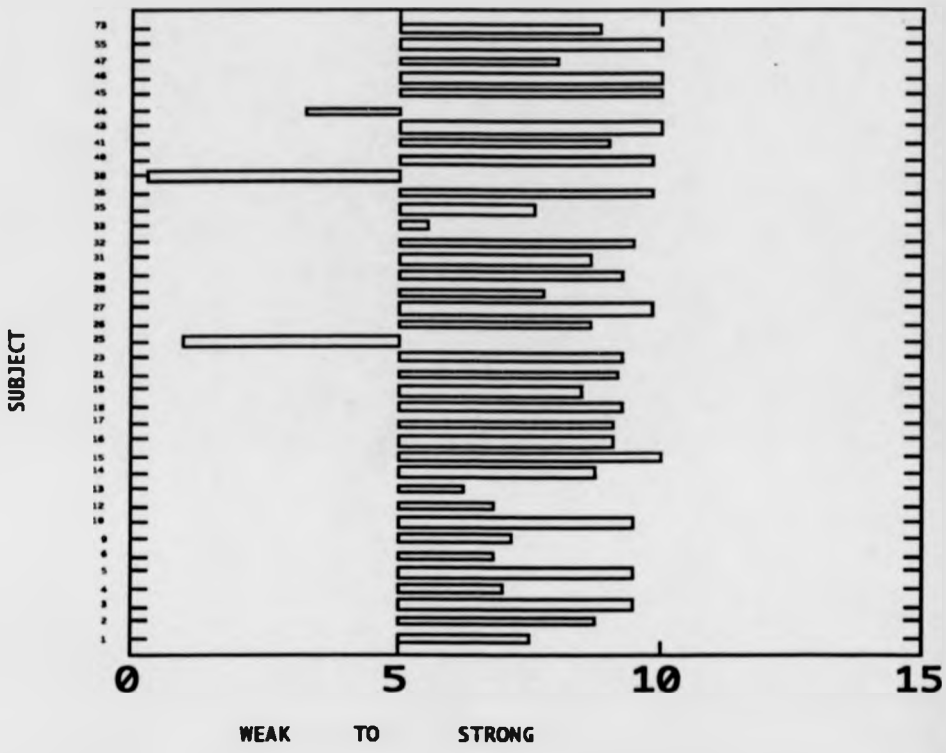
Subject ratings on the familiar-unfamiliar dimension for Traseolide



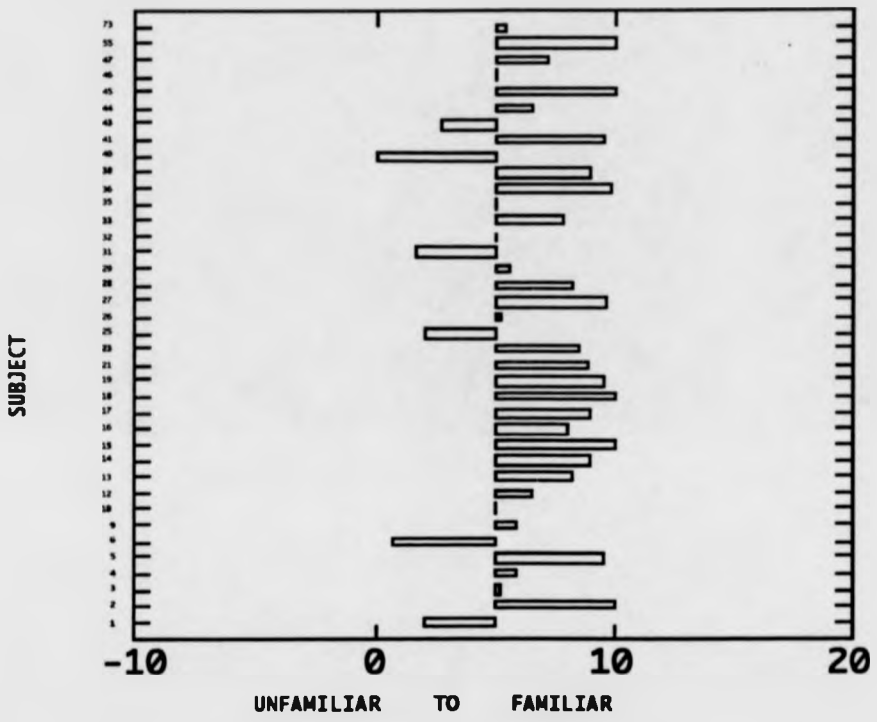
Subject ratings on the pleasant-unpleasant dimension for Iso-Valeric Acid



Subject ratings on the strong-weak dimension for Iso-Valeric Acid



Subject ratings on the familiar-unfamiliar dimension for Iso-Valeric Acid



Psychometric graphs of longitudinal data for 11 subjects, for each dimension, for each odour

The key for the graphs is shown below:

WTOS = STRENGTH

UNPTOP =PLEASANTNESS

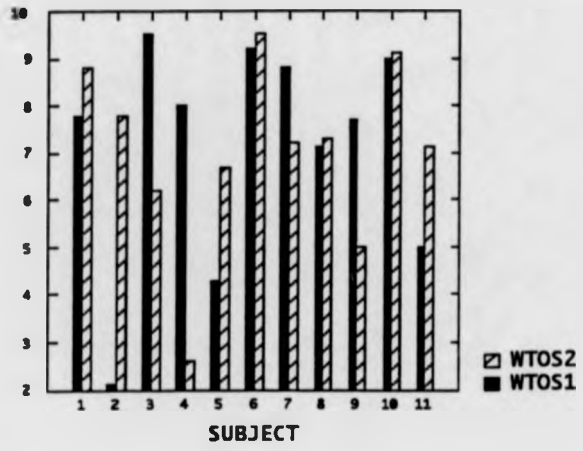
UNFTOF =FAMILIARITY

1= first testing session (black)

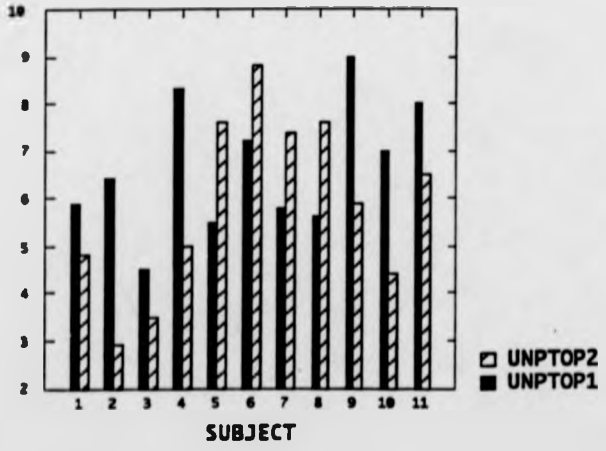
2=second testing session one year later. (shaded)

Vertices show the rating points (1-10)

BLUE DIAMOND

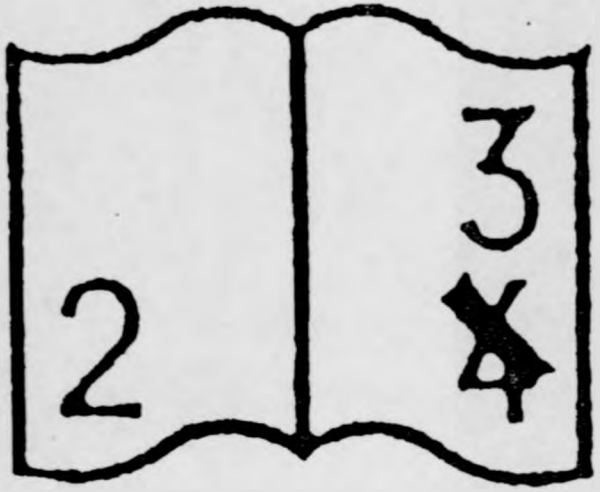


BLUE DIAMOND

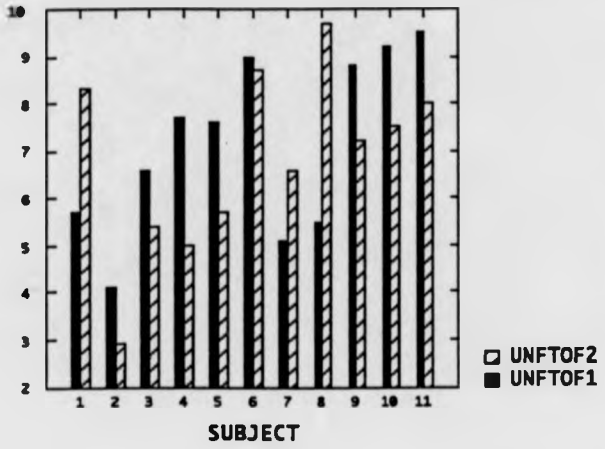


PAGINATION ERROR

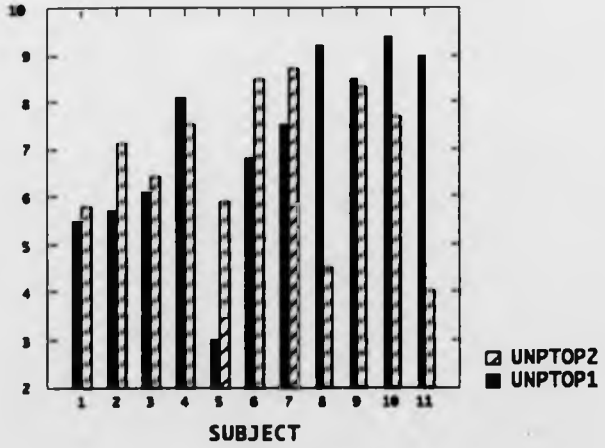
68, 69,



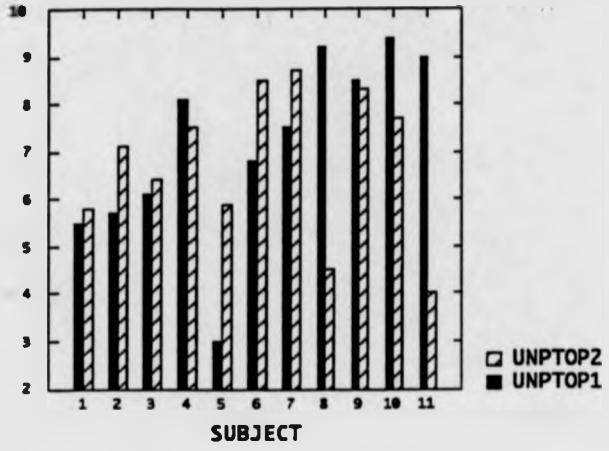
BLUE DIAMOND



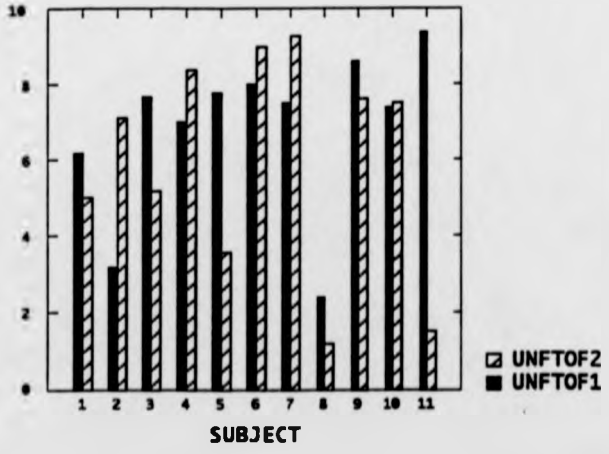
YELLOW TOPAZ



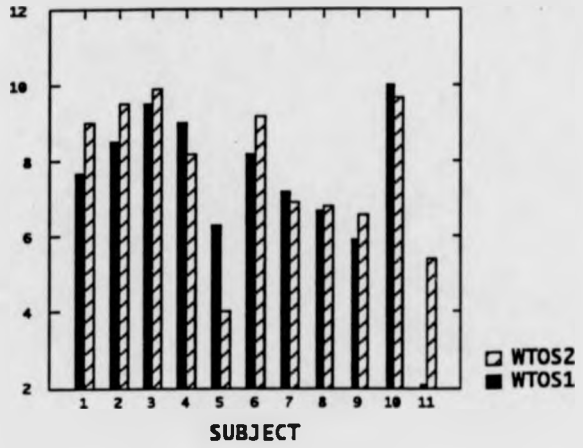
YELLOW TOPAZ



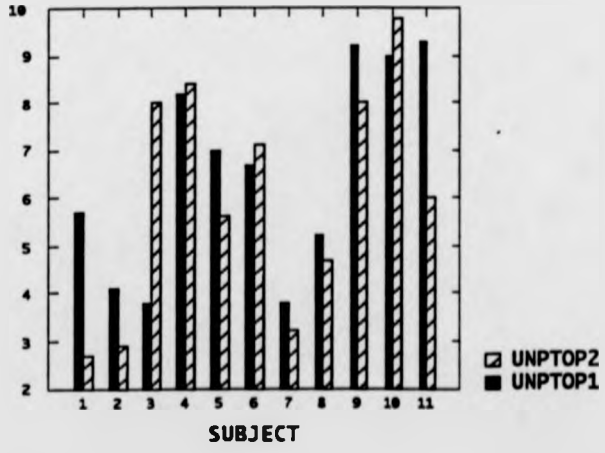
YELLOW TOPAZ



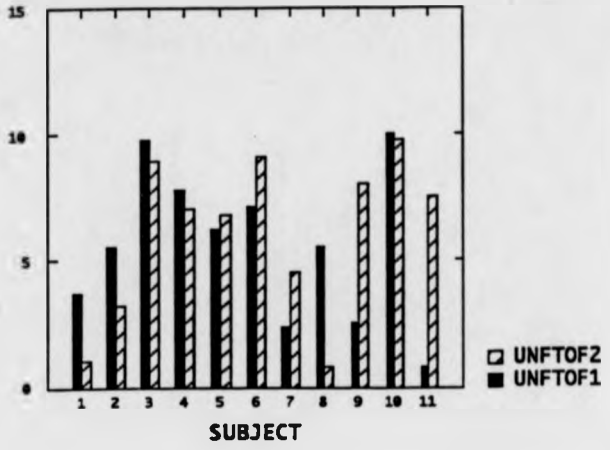
RED RUBY



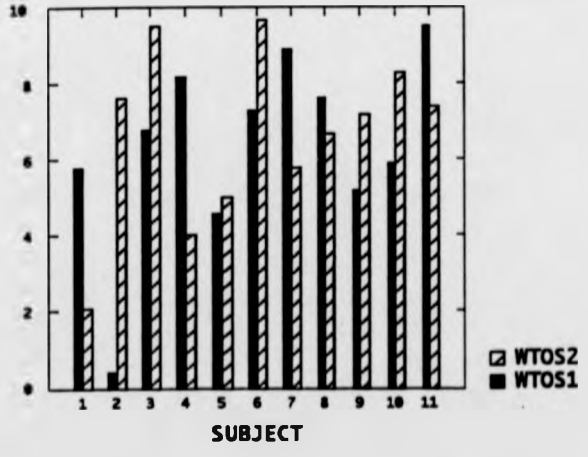
RED RUBY



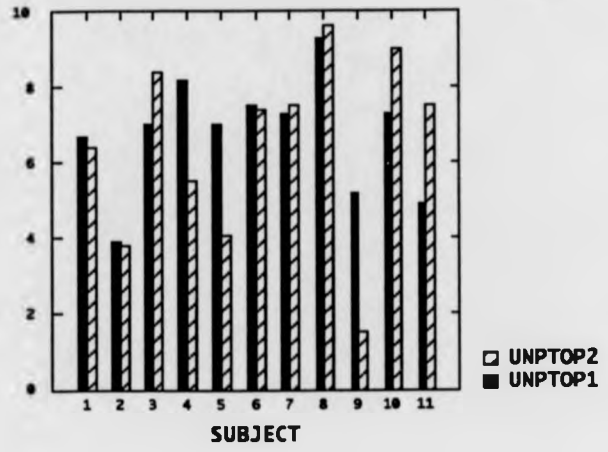
RED RUBY



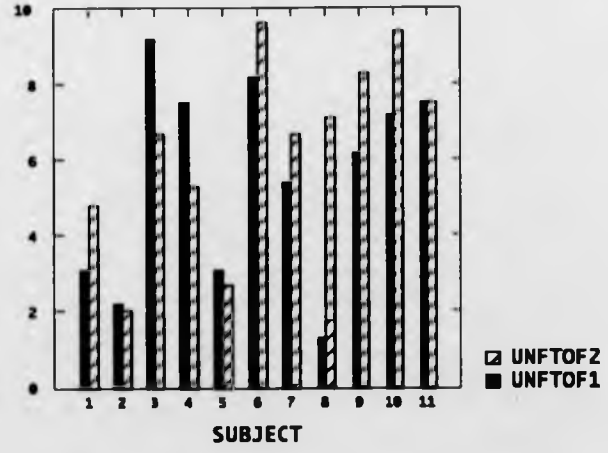
PINK QUARTZ



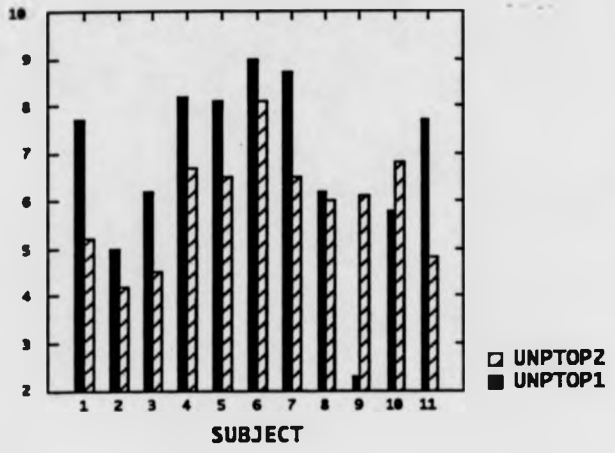
ANAIS ANAIS



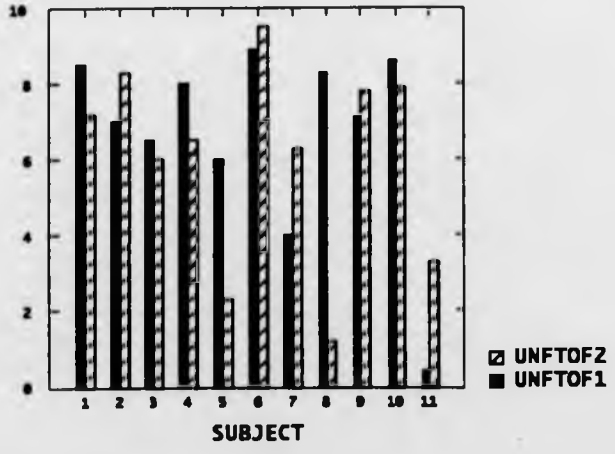
PINK QUARTZ



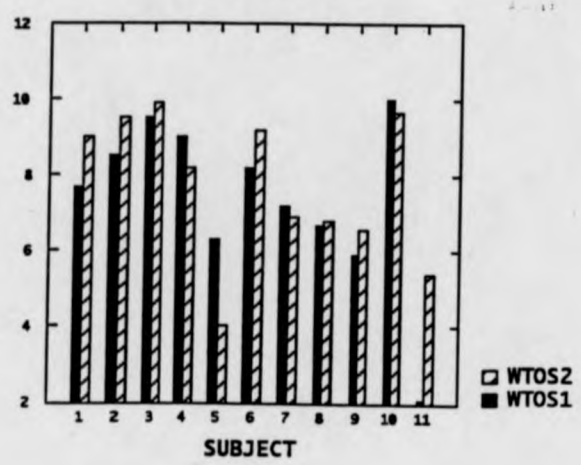
GOLDEN AMBER



GOLDEN AMBER

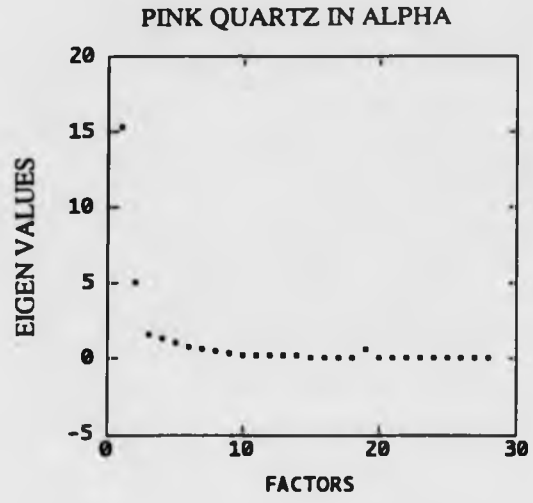


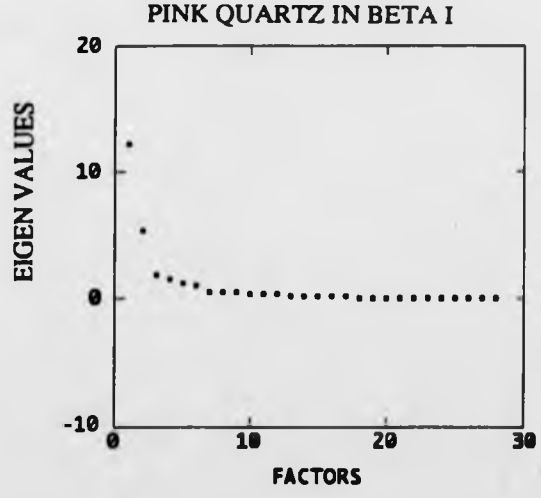
GOLDEN AMBER

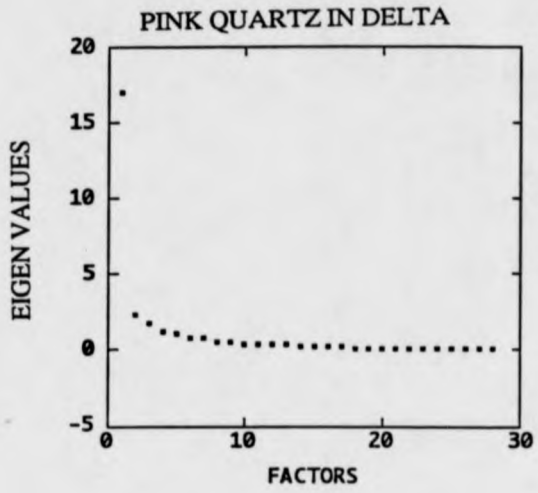


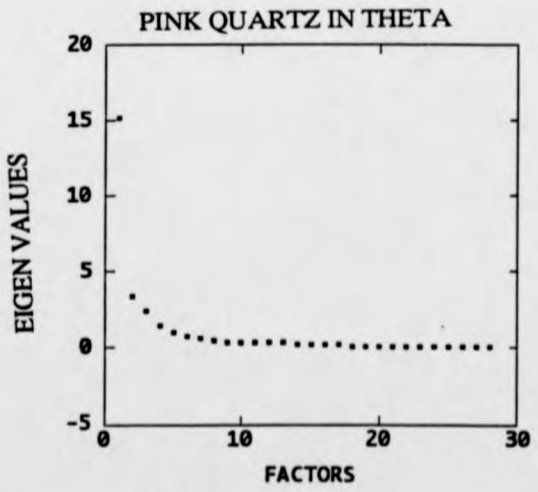
Scree plots for the six odours used in the principal component analysis in each waveband

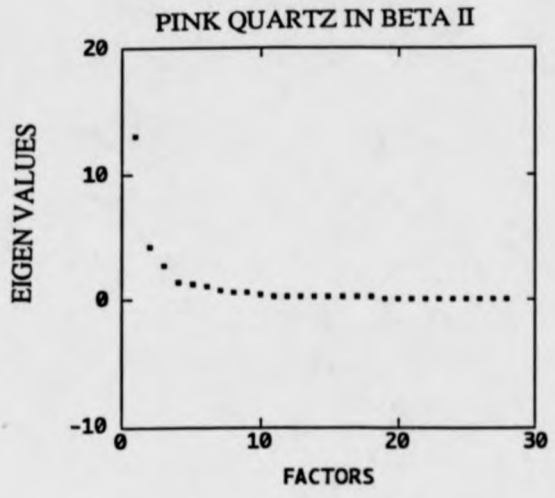
Scree diagrams

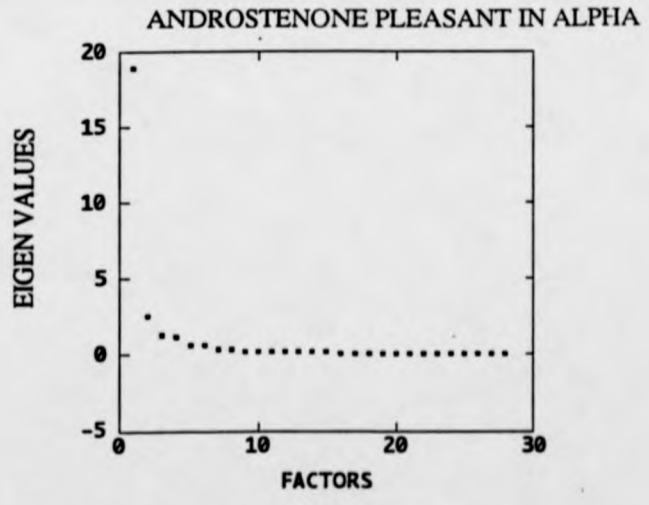




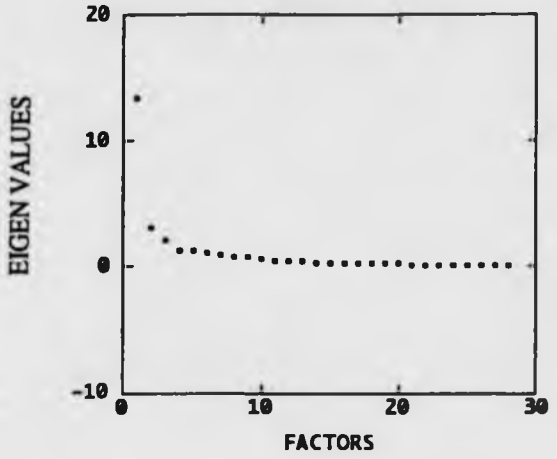

PINK QUARTZ IN DELTA
EIGEN VALUES
20
15
10
5
0
-5
0
10
20
30
FACTORS


PINK QUARTZ IN THETA
EIGEN VALUES
20
15
10
5
0
-5
0
10
20
30
FACTORS

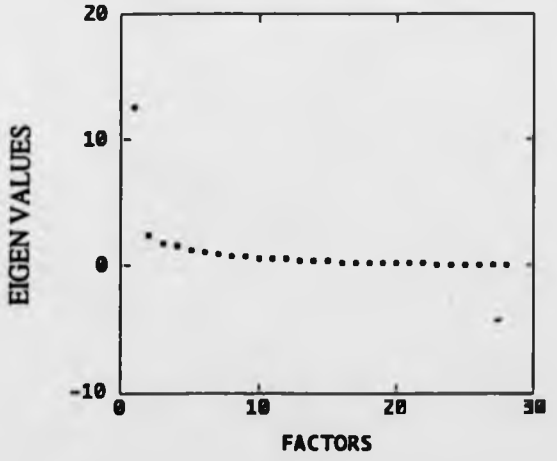

PINK QUARTZ IN BETA II
EIGEN VALUES
20
10
0
-10
0
10
20
30
FACTORS


ANDROSTENONE PLEASANT IN ALPHA
EIGEN VALUES
20
15
10
5
0
-5
0
10
20
30
FACTORS

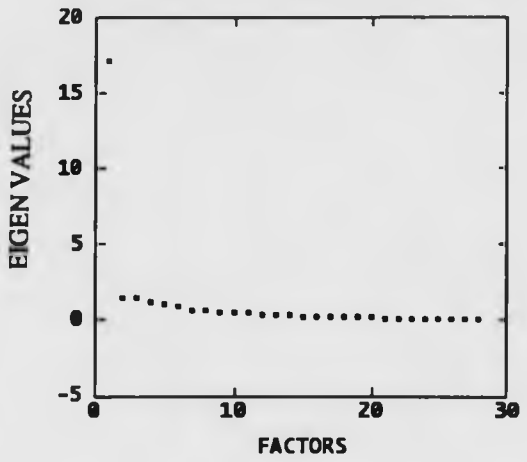
ANDROSTENONE PLEASANT IN BETA II



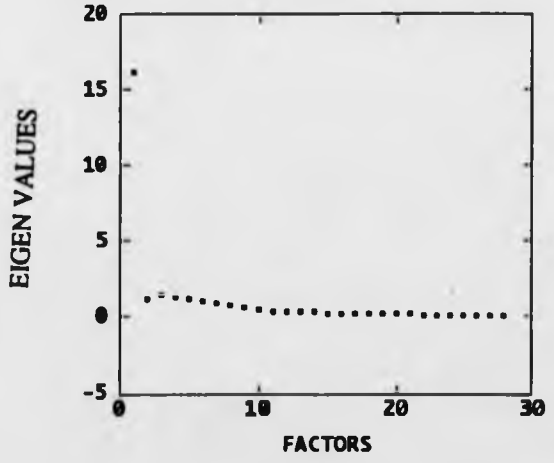
ANDROSTENONE PLEASANT IN BETA I



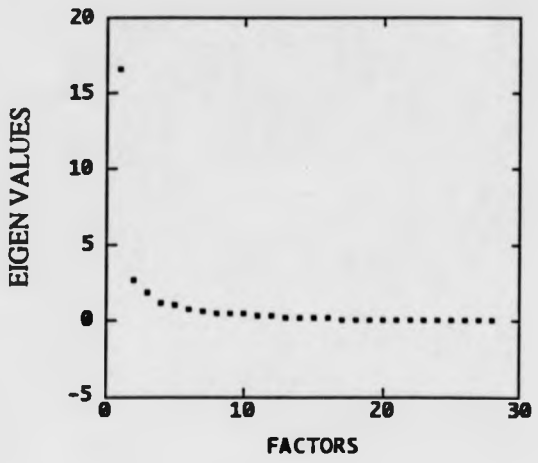
ANDROSTENONE PLEASANT IN DELTA



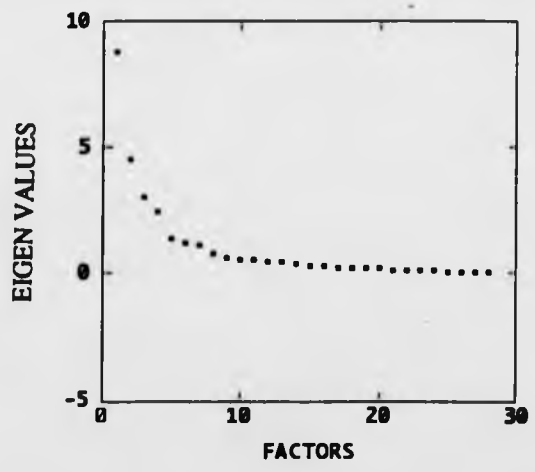
ANDROSTENONE PLEASANT IN THETA



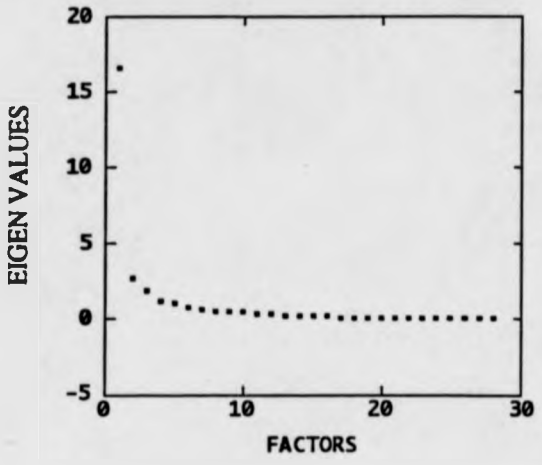
ANDROSTENONE UNPLEASANT IN ALPHA



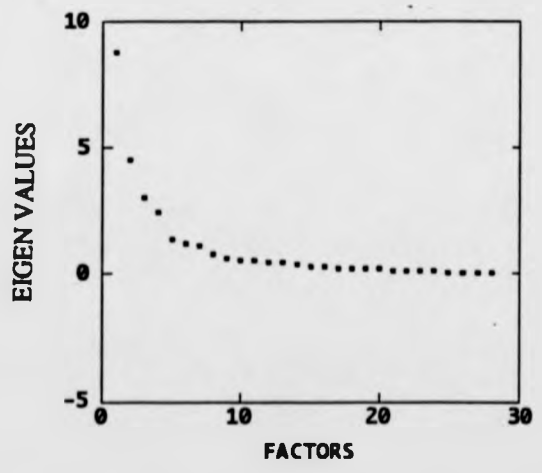
ANDROSTENONE UNPLEASANT IN BETA II



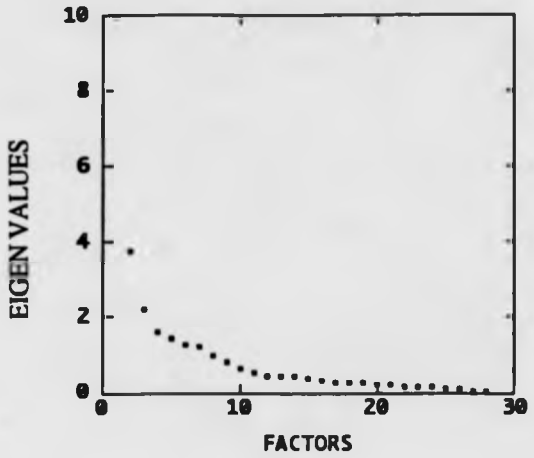
ANDROSTENONE UNPLEASANT IN ALPHA



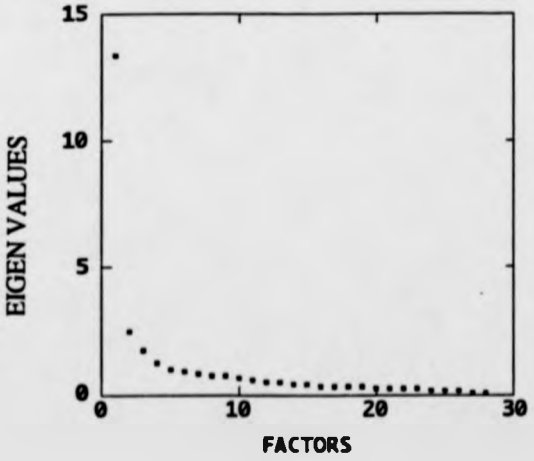
ANDROSTENONE UNPLEASANT IN BETA II



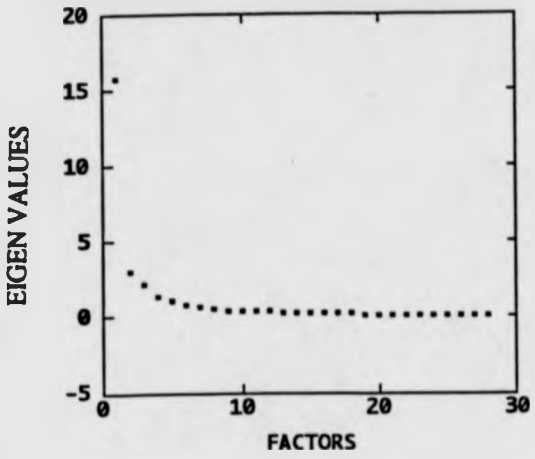
ANDROSTENONE UNPLEASANT IN BETA I



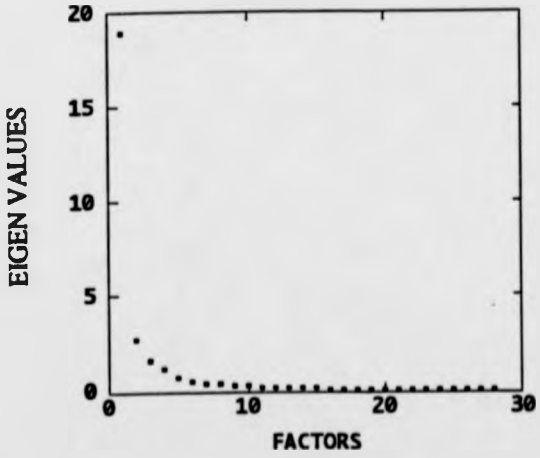
ANDROSTENONE UNPLEASANT IN DELTA



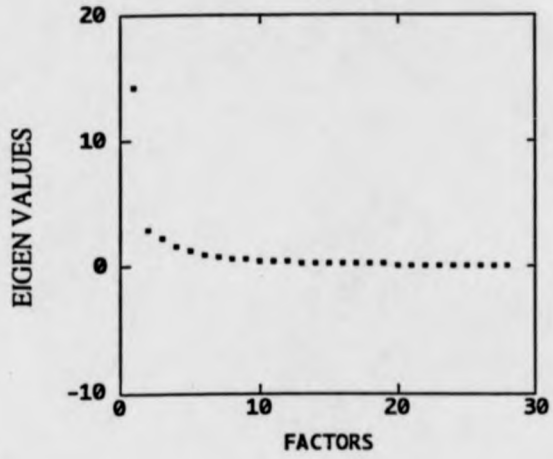
ANDROSTENONE UNPLEASANT IN THETA



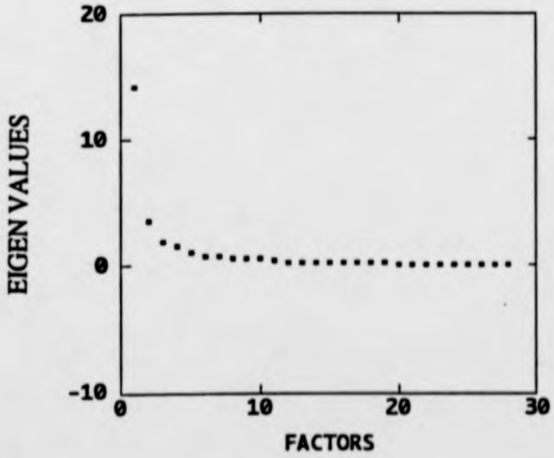
IVA IN ALPHA

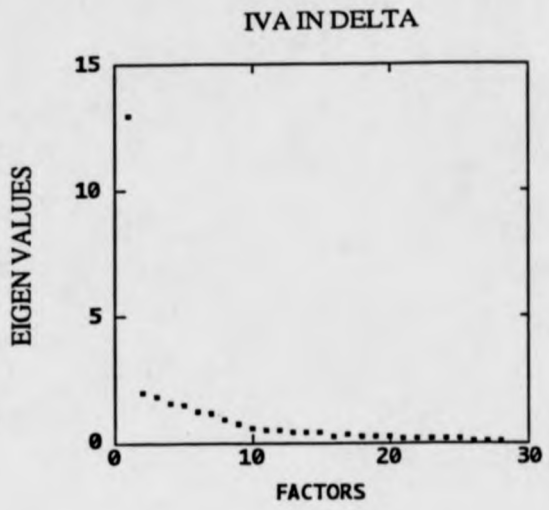


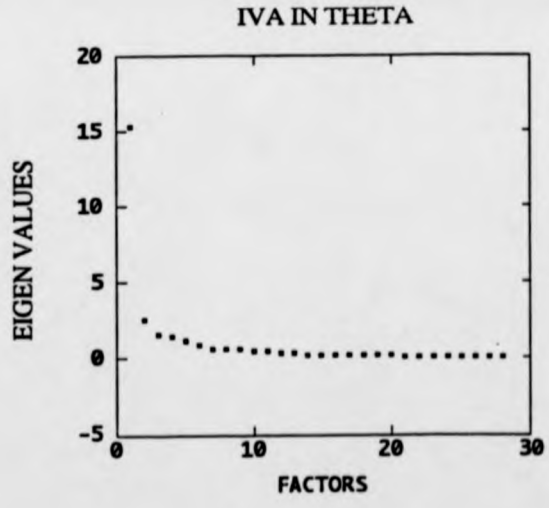
IVA IN BETA II



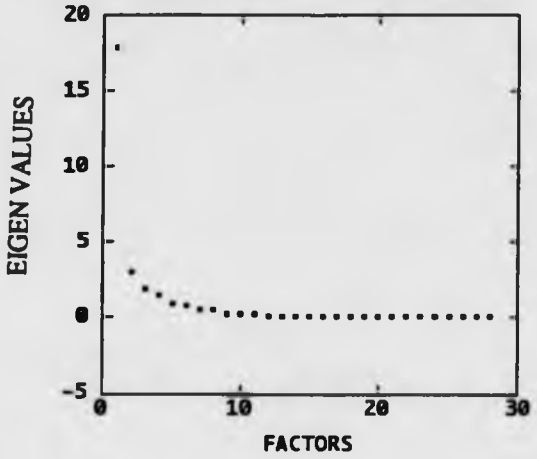
IVA IN BETA I



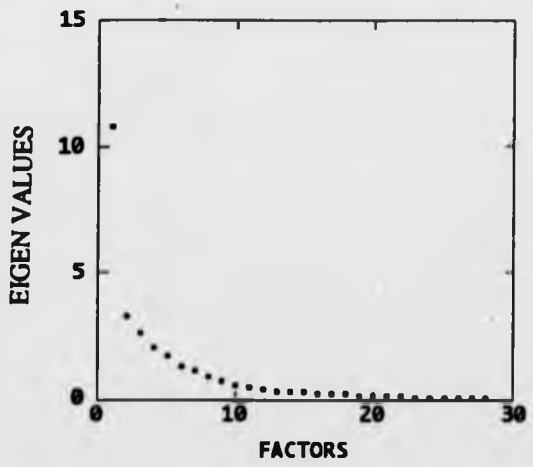

IVA IN DELTA
EIGEN VALUES
15
10
5
0
0
10
20
30
FACTORS


IVA IN THETA
EIGEN VALUES
20
15
10
5
0
-5
0
10
20
30
FACTORS

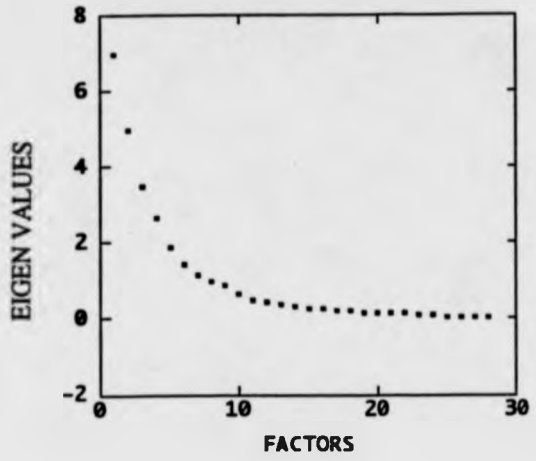
LINALYL ACETATE IN ALPHA



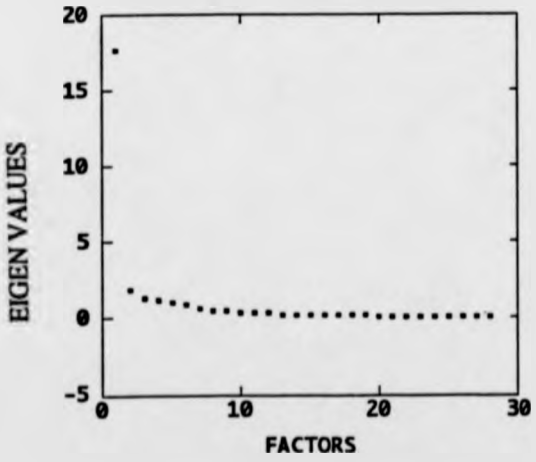
LINALYL ACETATE IN BETA I



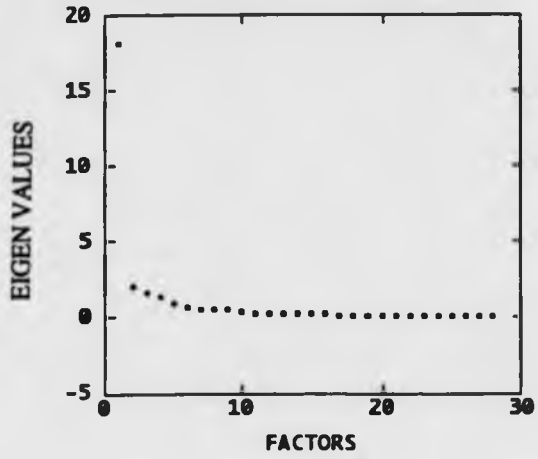
LINALYL ACETATE IN BETA II



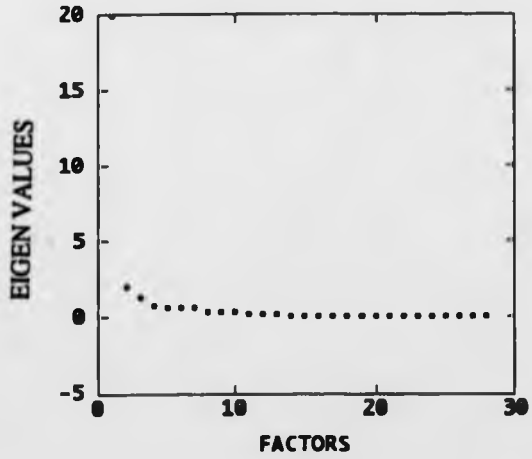
LINALYL ACETATE IN DELTA



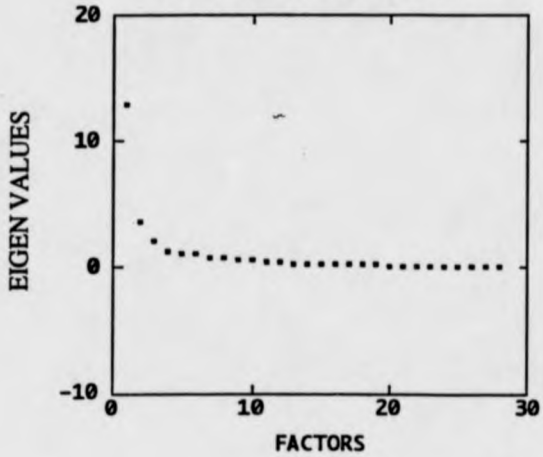
LINALYL ACETATE IN THETA



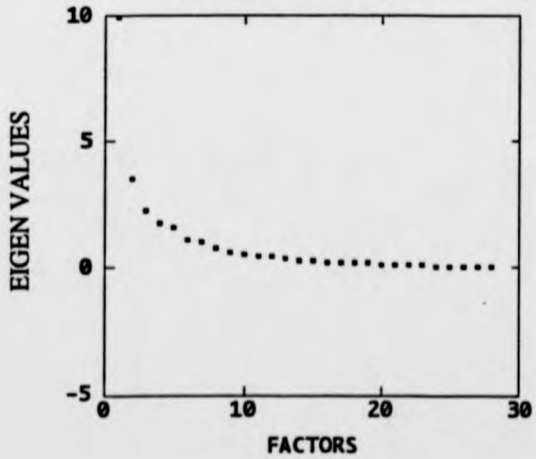
TRASEOLIDE IN ALPHA

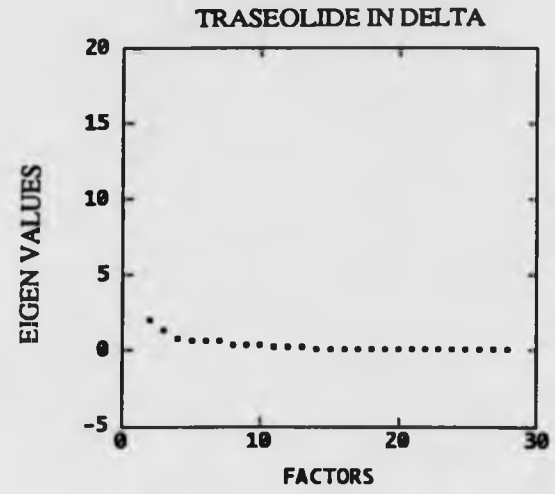


TRASEOLIDE IN BETA I



TRASEOLIDE IN BETA II




TRASEOLIDE IN DELTA
EIGEN VALUES
20
15
10
5
0
-5
0
10
20
30
FACTORS

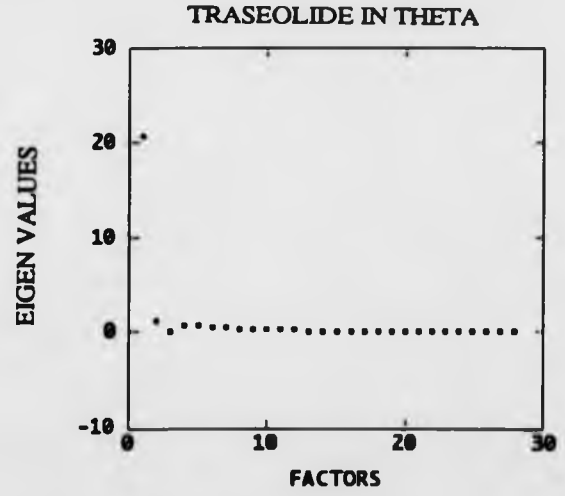
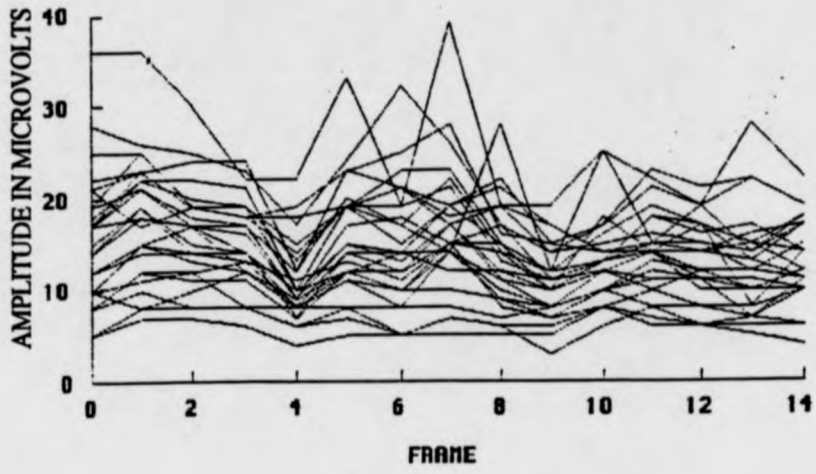
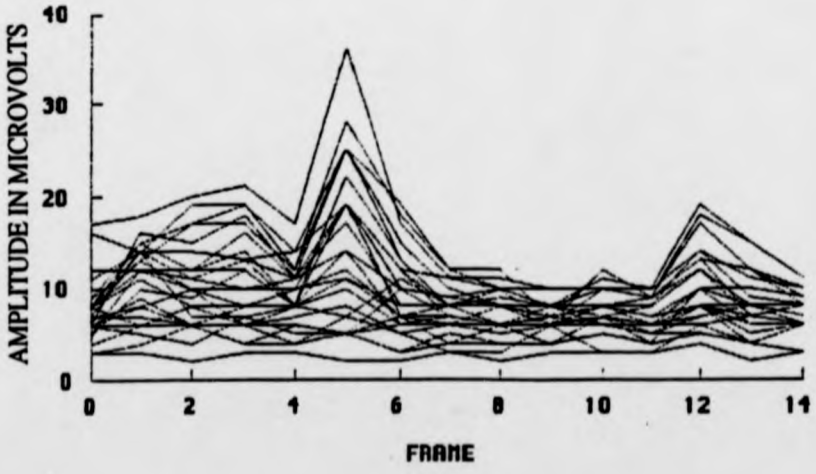

TRASEOLIDE IN THETA
EIGEN VALUES
30
20
10
0
-10
0
10
20
30
FACTORS

Figure 2.5.1 Example of the amplitude data in graphical form used in the reliability study





First sorted principal component loadings in delta, beta I and beta II.

Imperial Jade

Electrode	Delta	Electrode	Beta I	Electrode	Beta II
FTC2	.955	CP2	.833	PZ	.813
FTC1	.932	PZ	.791	CP2	.810
TCP1	.907	PO1	.777	CP1	.728
CP2	.907	CZ	.770	FZ	.726
PZ	.907	C4	.751	FZ	.726
FZ	.885	TCP2	.750	PO2	.678
PO1	.885	FTC2	.700	F3	.643
CP1	.871	PO2	.689	CZ	.618
T5	.870	P3	.670	TCP1	.616
TCP2	.865	TCP1	.657	TCP2	.612
T6	.860	FZ	.635	O2	.604
FP2	.860	FP2	.625	FTC1	.602
OZ	.821	O2	.613	PO1	.539
P3	.792	FP1	.605	C4	.582
O1	.789	T3	.598	T3	.566
FP1	.784	F3	.590	FTC2	.561
F8	.783	P4	.569	F7	.531
T3	.778	C3	.563	C3	.513
P4	.753	OZ	.561	T5	.505
C4	.751	O1	.555	FP2	.504
CZ	.714	FTC1	.517	P3	.504
O2	.708	F4	.407	P4	.500
C3	.648	CP1	.302	F4	.195
F7	.636	T5	.454	T4	.394
PO2	.621	T6	.460	F8	.425
F3	.616	F8	.483	O1	.216
T4	.593	F7	.494	OZ	.362
F4	.495	T4	.497	T6	.146

Blue Diamond

Electrode	Delta	Electrode	Beta I	Electrode	Beta II
FTC2	1.050	FTC2	.988	FTC2	.934
TCP2	.967	TCP2	.934	TCP2	.933
FTC1	.961	CP2	.921	C3	.923
PZ	.949	C4	.911	P3	.920
P4	.933	T3	.909	PO1	.913
CP2	.928	CZ	.906	FZ	.911
FZ	.926	CP1	.898	FP1	.898
T3	.918	O2	.898	F4	.898
FP1	.909	F4	.890	F7	.895
PO2	.900	O1	.881	C4	.893
C4	.899	P3	.880	CZ	.889
F4	.894	F7	.872	FTC1	.888
PO1	.892	PZ	.866	T6	.887
F8	.891	FZ	.863	PZ	.884
P3	.882	T6	.860	F3	.882
T6	.882	FTC1	.859	O1	.877
OZ	.868	T5	.853	CP2	.869
C3	.861	C3	.844	FP2	.863
O1	.859	PO2	.831	T5	.863
FP2	.855	PO1	.829	F8	.855
O2	.847	FP2	.827	P4	.842
T4	.845	FP1	.826	T3	.836
TCP1	.787	F3	.816	O2	.829
F7	.755	F8	.816	OZ	.814
F3	.745	P4	.814	TCP1	.767
CP1	.726	OZ	.778	PO2	.767
T5	.725	TP1	.778	CP1	.367
CZ	.690	T4	.724	T4	.400

Pink Quartz

Electrode	Delta	Electrode	Beta I	Electrode	Beta II
TCP2	.915	C4	.861	F3	.899
FTC1	.907	TCP2	.789	C4	.877
TCP1	.877	TCP1	.782	FP1	.866
C4	.876	F3	.766	FTC1	.846
F3	.870	T6	.751	T5	.817
T3	.870	T5	.738	FP2	.812
FZ	.869	P3	.723	TCP1	.799
OZ	.869	CP1	.720	F7	.798
T6	.864	PZ	.710	F8	.791
T4	.849	FTC1	.707	CP1	.779
PZ	.842	F4	.706	TCP2	.773
FTC2	.817	FP2	.706	FZ	.746
T5	.791	CZ	.702	CZ	.744
O2	.780	FP1	.695	P3	.719
C3	.760	F8	.673	PZ	.673
F4	.756	T3	.663	T6	.667
F8	.744	C3	.643	PO2	.664
CP1	.742	FZ	.643	C3	.605
FP1	.735	P4	.637	FTC2	.587
PO2	.721	T4	.622	F4	.585
CP2	.720	PO2	.611	P4	.558
PO1	.716	FTC1	.605	T4	.552
FP2	.688	OZ	.586	T3	.512
P3	.687	CP2	.501	O1	.154
CZ	.676	PO1	.456	PO1	.253
O1	.636	O1	.327	O2	.286
F7	.533	O2	.352	OZ	.495
P4	.525	F7	.449	CP2	.468

Traseolide

Electrode	Delta	Electrode	Beta I	Electrode	Beta II
PZ	.918	C4	.859	F7	.793
TCP2	.913	TCP2	.826	C3	.791
C4	.904	CZ	.851	FTC2	.766
F4	.900	F7	.799	P3	.762
OZ	.862	FTC2	.757	PZ	.750
O1	.851	F4	.754	TCP2	.719
T3	.843	O1	.748	O1	.707
P4	.840	FZ	.748	F3	.686
T4	.835	CP2	.747	FP1	.679
TCP1	.822	OZ	.742	CZ	.677
O2	.821	PZ	.738	FP2	.640
C3	.807	PO1	.727	P4	.640
F8	.799	O2	.725	F4	.632
FTC1	.799	FP1	.719	CP2	.630
F3	.793	F3	.716	FTC1	.624
FZ	.772	TCP1	.711	PO2	.621
T5	.751	T6	.705	FZ	.605
CZ	.736	C3	.670	T6	.605
FP2	.734	FTC1	.661	TCP1	.601
F7	.724	FP2	.655	OZ	.582
PO1	.688	F8	.633	PO1	.560
PO2	.673	P4	.629	T5	.141
FTC2	.663	T3	.613	F8	.440
CP2	.655	T4	.575	T4	.208
P3	.631	PO2	.525	CP1	.251
CP1	.609	T5	.525	T3	.210

Iso-Valeric Acid

Electrode	Delta	Electrode	Beta I	Electrode	Beta II
TCP2	.860	PO1	.865	F7	.864
PO1	.843	O2	.848	FTC1	.859
FTC1	.843	PZ	.847	PZ	.824
T3	.833	T5	.829	C4	.819
T4	.826	PO2	.824	O2	.806
01	.806	P4	.819	TCP2	.805
O2	.788	P3	.801	C3	.794
F3	.779	OZ	.788	CZ	.792
PZ	.759	CP2	.783	FTC2	.790
CZ	.757	F7	.773	T4	.779
C3	.742	CZ	.765	FP1	.777
OZ	.699	TCP2	.761	P4	.771
T5	.698	O1	.757	OZ	.758
F4	.688	T6	.739	PO2	.747
FP2	.674	TCP1	.728	T5	.726
P4	.673	FTC2	.718	F3	.718
TCP1	.666	C4	.716	F8	.716
FZ	.652	FP1	.677	F4	.695
PO2	.636	T3	.664	PO1	.682
FP1	.622	C3	.652	TCP1	.677
FTC2	.574	T4	.619	T3	.673
CP2	.571	F3	.588	FP2	.661
T6	.502	FTC1	.535	P3	.600
F7	.482	F4	.529	FZ	.597
CP1	.474	FP2	.528	CP2	.550
P3	.190	FZ	.523	CP1	.125
C4	.454	CP1	.421	T6	.464
F8	.474	F8	.498	O1	.420

Linalyl Acetate

Electrode	Delta	Electrode	Beta I	Electrode	Beta II
TCP2	.929	CZ	.833	CZ	.787
O1	.928	PZ	.815	PZ	.770
T4	.907	TCP2	.806	C3	.713
C4	.905	PO1	.796	CP3	.664
OZ	.904	CP2	.795	C4	.612
O2	.904	O2	.778	P3	.579
PZ	.891	PO2	.730	PO1	.568
CZ	.890	OZ	.703	TCP2	.540
FTC1	.860	P4	.696	P4	.516
PO1	.859	C4	.693	T3	.508
T5	.847	T6	.667	FTC2	.503
C3	.831	P3	.665	O2	.500
FZ	.806	FTC2	.622	FTC1	.464
P4	.796	F8	.594	F3	.467
F8	.788	C3	.591	F4	.428
PO2	.773	T3	.558	F7	.444
T6	.760	F7	.540	T4	.398
P3	.757	TCP1	.532	OZ	.333
FP1	.748	FTC1	.527	O1	.101
FTC2	.740	T4	.520	FZ	.488
T3	.736	F4	.462	T5	.413
FP2	.720	F3	.498	FP2	.401
CP1	.707	FZ	.498	CP1	.142
F7	.679	FP1	.359	TCP1	.181
F3	.638	FP2	.455	T6	.444
CP2	.590	01	.485	FP1	.400
TCP1	.589	CP1	.171	F8	.372
F4	.532	T5	.464	PO2	.487

Androstenone "Pleasant"

Electrode	Delta	Electrode	Beta I	Electrode	Beta II
PO1	.908	FTC1	.801	FTC2	.876
O1	.889	C4	.779	C4	.850
C3	.886	O1	.776	OZ	.830
P3	.882	P3	.763	F7	.829
T3	.880	C3	.761	FTC1	.829
FTC1	.860	F7	.754	P3	.817
TCP2	.849	PO2	.743	O2	.808
C4	.844	OZ	.739	PO2	.763
FP2	.842	CZ	.733	TCP2	.752
OZ	.839	O2	.720	T6	.748
FP1	.837	FP2	.711	01	.730
O2	.836	PZ	.685	PZ	.724
TCP1	.815	FTC2	.675	CZ	.723
CP1	.804	F4	.645	TCP1	.682
CP2	.804	T5	.651	F8	.658
CZ	.794	CP2	.647	P4	.656
PZ	.793	FP1	.634	FP1	.641
T5	.773	F3	.627	FP2	.634
FZ	.771	T6	.619	C3	.630
F3	.744	PO1	.582	CP1	.627
F7	.741	FZ	.571	T5	.622
T4	.726	TCP2	.568	F4	.608
F4	.708	T3	.548	T4	.564
T6	.666	F8	.520	F3	.562
P4	.628	T4	.548	CP2	.508
F8	.602	T6	.619	FZ	.465
PO2	.504	CP1	.498	T3	.493
FTC2	.421	P4	.493	PO1	.404

Androstenone "UnPleasant"

Electrode	Delta	Electrode	Beta I	Electrode	Beta II
PZ	.844	C4	.811	C4	.857
OZ	.801	CZ	.804	CP2	.787
TCP2	.789	PZ	.760	C3	.782
PO2	.787	C3	.730	PZ	.780
P4	.782	TCP1	.724	CZ	.761
C3	.782	CP2	.710	FZ	.707
PO1	.781	FP2	.702	P3	.704
T6	.779	P3	.691	FP1	.689
P3	.744	FZ	.686	FP2	.618
TCP1	.740	F8	.683	PO1	.596
FZ	.722	FTC2	.675	TCP1	.595
CZ	.716	FP1	.675	F8	.594
T5	.698	PO1	.634	TCP2	.570
T4	.693	TCP2	.557	FTC2	.560
O2	.686	O2	.554	FTC1	.308
FP1	.658	T3	.525	F4	.339
C4	.659	F7	.520	F3	.423
F8	.656	F3	.509	F7	.487
FTC1	.641	F4	.470	T5	.305
O1	.634	FTC1	.425	T3	.423
CP2	.627	P4	.474	T4	.223
FP2	.626	CP1	.297	T6	.454
T3	.598	PO2	.470	CP1	.335
F4	.578	OZ	.474	O1	.348
CP1	.561	T4	.381	OZ	.357
FTC2	.552	O1	.472	P4	.459
F3	.533	T6	.474	O2	.443
F7	.497	T5	.369	PO2	.368

Percentage of variance accounted for by the first, second and third principal components, by odour, in delta, beta I and beta II.

Odour	1st	2nd	3rd	Waveband
Pink Quartz	60%	8%	6%	Delta
	44%	19%	7%	Beta I
	46%	15%	10%	Beta II
Imperial Jade	63%	13%	21%	Delta
	38%	14%	9%	Beta I
	33%	14%	11%	Beta II
Blue Diamond	76%	5%	3%	Delta
	74%	8%	3%	Beta I
	72%	6%	5%	Beta II
Traseolide	62%	6%	5%	Delta
	48%	13%	8%	Beta I
	38%	14%	9%	Beta II
I.V.A	46%	7%	6%	Delta
	51%	13%	7%	Beta I
	51%	10%	8%	Beta II
Linalyl Acetate	63%	6%	5%	Delta
	39%	12%	10%	Beta I
	25%	18%	12%	Beta II
Androst."Pleas"	61%	5%	5%	Delta
	45%	9%	6%	Beta I
	48%	11%	8%$	Beta II
And."Unpleas"	48%	9%	6%	Delta
	36%	4%	2%	Beta I
	31%	16%	11%	Beta II

Results from discriminant analyses.

Below are listed the univariate F-tests for the effect of odour, in the discriminant analysis. Results are given for each electrode.

Electrode	F-statistic	P-value
FP1	1.292	0.268
FZ	1.028	0.401
CZ	1.323	0.255
PZ	2.943	0.013
OZ	5.780	0.000
F3	4.189	0.001
C3	1.663	0.144
P3	4.745	0.000
O1	5.178	0.000
F7	2.369	0.040
T3	1.273	0.276
T5	2.734	0.020
FTC1	3.000	0.012
TCP1	2.020	0.076
CP1	0.393	0.853
PO1	4.762	0.000
FP2	1.935	0.089
F4	8.452	0.000
C4	2.373	0.039
P4	2.481	0.032
02	4.937	0.000
F8	3.990	0.002
T4	3.236	0.007
T6	2.373	0.039
FTC2	3.127	0.009
TCP2	3.672	0.003
CP2	2.321	0.007
PO2	4.573	0.001

The multivariate test results are as follows:

Wilks Lambada	= 0.181		
F- Statistic	= 3.614	DF = 140, 1224	p = 0.000
Pillai Trace	= 1.388		
F-Statistic	= 3.446	DF = 140, 1255	p = 0.000
Hotelling-Lawley Trace	= 2.150		
F-Statistic	= 3.769	DF = 140, 1227	p = 0.000

This demonstrates that the discriminant analysis can discriminate between the odour samples on the basis of the electrode values. However, the results shown below suggest the artifactual nature of this result, as there is no interaction between odour and before and after presentation of the odour. A significant interaction would be a prerequisite for being able to interpret the above results in terms of the aim of the analysis.

Electrode	F-statistic	P-value
FP1	1.043	0.393
FZ	0.406	0.844
CZ	0.707	0.619
PZ	1.071	0.377
OZ	0.871	0.501
F3	0.585	0.711
C3	0.728	0.603
P3	0.811	0.543
O1	0.638	0.671
F7	0.868	0.503
T3	0.638	0.671
T5	0.906	0.477
FTC1	0.409	0.842
TCP1	0.753	0.585
CP1	0.949	0.450
PO1	0.672	0.645
FP2	0.644	0.667
F4	0.739	0.595
C4	0.526	0.756
P4	1.028	0.402

02	0.698	0.625
F8	0.261	0.934
T4	0.747	0.589
T6	0.704	0.621
FTC2	0.429	0.782
TCP2	0.940	0.455
CP2	0.767	0.574
PO2	0.639	0.670

The multivariate test results are as follows:

Wilks Lambada	= 0.635		
F- Statistic	= 0.844	DF = 140, 1224	p = 0.899
Pillai Trace	= 0.432		
F-Statistic	= 0.847	DF = 140, 1255	p = 0.895
Hotelling-Lawley Trace	= 0.480		
F-Statistic	= 0.841	DF = 140, 1227	p = 0.904