Neurophysiology of Ingestion

Edited by

D. A. BOOTH

Preface

This book is centred on electrical recordings from single neurones that are related to the control of food or drink consumption. This is because of my conviction that unit recording is the key to understanding how the brain works.

There has been half a century of vigorous research into the neuroscience of intake. Obese or self-starving rats with damage in the hypothalamus have been famous among generations of students of psychology and neurobiology. Nevertheless, this book is the first to focus on bringing together the major contributions of integrative cellular neurophysiology to the understanding of the neural bases of mammalian eating and drinking behaviour. The reader is invited to consider how important a step in the right direction the appearance of this little volume might be.

The book is written for scientists and students who are interested in the brain mechanisms of eating and drinking, whether or not they work in neuroscience or ingestive behaviour. The chapter authors have been encouraged to review their own and others' research on a particular aspect of ingestive neuroscience in a way that is accessible to biological or behavioural scientists in other areas, but that can also serve to update colleagues working on other aspects of the neural bases of food and water intake and choice.

I am most grateful to my fellow authors for the enthusiasm, dedication and patience that they have shown during this enterprise. Also, without the invitation from Bill Winlow to contribute to the Pergamon Studies in Neuroscience series, this sort of book would still not have been produced, under my editorship at least.

Food and drink are fun. Research is a highly involving activity. Communication of ideas can bring great satisfaction when it materialises in print. I hope that readers too will share the pleasures of chewing over and digesting these issues about how we eat and drink, while regularly continuing to enjoy ingestive activity itself!

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A framework for neurophysiological studies of ingestion

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The neuroscience of ingestion is a long-established and vigorous area of research activity, represented in many of the textbooks. Intakes of food and drink became a topic for experiments on the brain in the 1940s, before electrical recording from nerve cells was generally feasible. In 1962, at the first conference on food and fluid intake as a satellite to the Congress of the International Union of Physiological Sciences, much of the work reported involved lesions or stimulation of rats' brains. Since 1970, Feeding and Drinking or, latterly, Ingestive Behaviour has been an area with its own series of sessions at the annual meetings of the Society for Neuroscience.

Yet research into the neural mechanisms of vertebrate food and water intake has not been obviously part of the mainstream of brain research. Invertebrate ingestion has been closer to other neuroscience but has had few links with intake by mammals and birds.

The 1940s also saw the beginning of theoretical work on the embodiment of cognitive functions in cellular interactions within a nervous system linked to its environment. This start on a mechanistic science of brain and behaviour was based on considerable neuroanatomical evidence and early findings from cellular electrophysiology. When the technique of unit recording became more widely applicable in the 1960s, systematic detail could be collected which has provided the foundation for a fully fledged science of integrative neurophysiology.

However, the psychologists and biologists of vertebrate intake rather seldom attempted to relate their research to evidence on what the nerve cells actually did. Neither theories nor data on the electrical activity of systems of neuronal units have been a major or central theme in the research journals or textbook chapters on the physiology of hunger and thirst. Yet nobody doubts that interactions among cellular networks in the brain provide a key physical basis for eating and drinking behaviour.

There are now well-established techniques for single-cell recording within the brain of conscious and moving animals. A good number of neurophysiological laboratories have worked on particular aspects of systems involved in ingestive behaviour. Nevertheless, it remains a severe challenge to relate the results effectively to functionally integrative mechanisms. Also, this sort of work tends to be scattered in specialized research literature, either of general neurophysiology or of the sensory system or other area of physiology to which the results also relate. This book appears to be the first to bring together the major electrophysiological contributions to the understanding of ingestive behaviour. It provides ready access to the approach for scientists and students who are more familiar with other techniques for investigating brain mechanisms of eating and drinking. It should also facilitate exchange among the neuroscientists who specialize in separate aspects of the neural systems of ingestion.

1.1. The centrality of neurophysiology

This book focuses on cellular neurophysiology. That is because of the editor's longstanding conviction that recording the electrical activity of functionally and anatomically identified single neurones is the central foundation of neuroscience.

No amount of molecular neuroscience, cognitive neuropsychology or neural network theory, by themselves or together, can tell us how the central nervous system works to perform its functions. Cellular biochemistry cannot tell us how the brain works as a whole. Even the most detailed analysis of the behavioural effects of interfering with the brain by anatomically or chemically specific damage, blockade or stimulation fails to show how neurones are transforming information. The most refined forms of neuropsychology and psychopharmacology can only test theories of mechanisms when these have already been built from microanatomical and electrical records that reveal the actual connections between nerve cells.

The electrophysiological analyses also need to be of integrative neuronal interactions. Unless we specify the manner in which the firing patterns in one relevant sort of neurone interact with those of other neurones to influence the firing of another sort of cell in a functional subsystem, we cannot build a realistic theory of the neural processes underlying the organization of behaviour. Indeed, for the purpose of determining how the processes in a critical region of the brain contribute to the organization of behaviour and cognition, the other neurosciences are tools for testing the hypotheses generated by integrative neurophysiology.

Molecular neuroscience in itself can at most tell us what nerve cells do. Cognitive neuropsychology by itself tells us only about how the mind works, better than we can know from undamaged brains. Parallel distributed processing calculations alone can only tell us what is logically possible. Neurophysiological research is the only way to work out how nerve cells interact with each other and with the environment in network systems that perform the functions of the brain. Solving the age-old brain–mind problem will depend on integrative cellular neurophysiology related to cognitive analysis of behavioural performance.

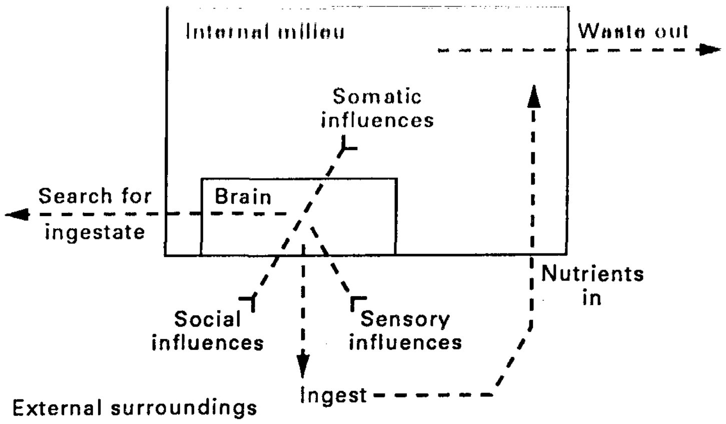

FIG. 1.1. The input/output relationships constituting ingestive behaviour.

In that spirit, the reader is invited to work through the specialized chapters that follow and catch a vision of what another half century of ingestive neuroscience could tell us about the brain and behaviour. Eating and drinking are not only fascinating in their own right. Their amenability to neurophysiological analysis makes them likely to be productive also of wider insights into the neural basis of behaviour.

1.2. Selection of appropriate ingestates

Ingestion is not just movements or amounts consumed. Ingestion is behaviour—that is to say, causal relationships between motor output and sensory input. Eating and drinking depend on the sensory control of reaching for the dietary material, its introduction into the mouth, chewing, transfer to the back of the mouth and swallowing (Fig. 1.1). This is evident from the fact that not every biteable solid or sippable fluid is ingested. Furthermore, even the materials that are not rejected on sight or smell, or spat out on tasting or feeling in the mouth, are selected, chewed and swallowed with varying degrees of apparent enthusiasm.

The intake of food and fluid therefore is not merely the disappearance of materials down the throat. Rather, each mouthful taken is the result of perceptual processing, both of sources of nutrition and of nutritional requirements of the body. The basic problem that needs explaining is how the searcher for food or drink knows when to eat or drink and what to ingest next, from information available in the external and internal environments. Investigating the control of each mouthful is closer to the timebase on which integrative neural processes operate than collecting data on amounts consumed in meals or over fixed periods.

Taking a drink, eating a food item and expressing dietary preferences all involve choices among materials according to their sensed characteristics. That is, items of food and drink must be discriminated and recognized. Hence, the technology of food and beverage formulation is indispensable to an effective sensory neurophysiology and psychology of eating and drinking. One of the most productive approaches to ingestive behaviour, predominant in this book, is the analysis of the oronasal senses involved.

In addition, however, choices among ingestates and decisions to start or stop consumption are at least to some degree coordinated to requirements for water, energy and other nutrients. This means that incipient states of need and repletion in the body must also be perceived in a way that enables appropriate action. Hence the visceral senses are also included.

In short, ingestion requires the recognition of items of food and drink, both from their sensory qualities and from predictable after-effects. This introductory chapter therefore outlines the problems that have to be solved by the eater's nervous system in recognizing foodstuffs and also in distinguishing bodily states in which it is appropriate to eat and to stop eating or indeed to take a drink (Booth, 1991).

1.3. Learning about foods

The detailed recognition of particular types of object and material by mammalian species is generally a learned performance. Some stimulus patterns are adequate to elicit behaviour innately. Yet even responses as reflexive as ingestion appears to be in normal and familiar situations are probably under control by patterns of stimulation that has been acquired by processes such as long-term habituation, associative conditioning and concept formation.

Both fixed reactions and instrumental acts towards food stimuli are conditionable in the infant rat within a few days of birth. Human babies can learn the smell, visual appearance and perhaps sound of the voice of their nursing mothers within a few weeks of birth at the most. Specifically to ingestion, there is evidence that human infants rapidly come to prefer the low level of sodium ions to which they have been exposed in breast milk, once the taste receptors have matured sufficiently for them to detect it (Harris, Thomas and Booth, 1991). Certainly, young rats that are beginning to feed spontaneously away from the dam learn to prefer whatever smell is given to energy- or protein-rich synthetic diets (Booth, Nicholls and Stoloff, 1974).

Human infants starting on solids learn to like salted foods and drinks if they are presented (Harris and Booth, 1985). Babies fed on sugar water still like plain sweetened water when they are 2 years old, unlike those who did not have that experience (Beauchamp and Moran, 1982).

These learned taste and odour preferences are not just for the sensory quality, however. They are specific to its intensity and also to the context of other sensory characteristics of the foodstuff. The older infant's preference is for the particular level of salt, for example, in the specific item of food or drink that has repeatedly been experienced with that level in it (Harris and Booth, 1987). Human adults show a sharp peak of preference among different salt levels in bread, close to the level generally marketed and experienced (Conner, Booth, Clifton and Griffiths, 1988). Similarly, in adult rats, the particular level of sweetness becomes preferred that has been associated with a higher level of osmotically mild carbohydrate calories (Booth, Lovett and McSherry, 1972).

1.3.1. Sweetness preferences and aversions

This calorically conditioned sweetness preference can completely overwhelm the unlearned liking for any sweetness (Booth *et al.*, 1972). This suppression of innate preference by learned preference is also evident in human adults. People come to like whichever level of sweetness is familiar in a particular food or drink. This level can differ widely between types of food. Yet, whatever the familiar level, samples of that food or drink containing appreciably higher levels of sweetness are less liked (independently of attitudes to sugars or artificial sweeteners) (Conner and Booth, 1988).

A newborn baby, by contrast, sucks more vigorously, consumes a larger amount and smiles more reliably the stronger is the sweetness placed on the tongue. This infantile reflex is also apparent in a child faced with an unfamiliar or disliked food that has been strongly sweetened. In adults too, when a familiar sweet drink is made very much sweeter than usual, the innate liking may break through despite the contrast with the level that has been learned to be preferred.

Also, the association of sweetness with effects of a poison or overdose of insulin will condition an aversion to sweetness (Lovett and Booth, 1970). At least with sufficiently moderate aversions, the most vigorous rejection is probably at the particular level of sweetness that was conditioned, while substantially higher and even perhaps lower concentrations are less aversive. Osmotic effects of hypertonic sugar solutions also condition aversions to hitherto attractive sweetness (Le Magnen, 1959; Booth *et al.*, 1972; Davis and Smith, 1990), evident as slowing of intake from the start of a test drink.

Hence, increasingly strong stimulation of sucrose-sensitive receptors and their afferents from the mouth is not necessarily transformed into increasing excitation of ingestatory movements. Depending on the learning history of the individual and on any other learned stimuli present, the response to a particular concentration of sucrose will be greater than to some higher or lower concentrations.

At which stage in the sensory and motor pathways this peak of recognition and preference is introduced by learning is a matter for neurophysiological investigation. It may differ between species and, within a species, between types of learning. For example, aversion conditioning alters the representation of sweetness at the first relay in the brainstem in the rat (Scott, Chapter 7). Yet the habituation-like type of satiation induced by exposure to sweetness is not represented in the monkey until the sensory pathway reaches association cortex (Rolls, Chapter 9).

1.3.2. Sensory norms in learned preferences

The learning-induced preference or aversion peak among sweetener concentrations is striking for the case of sweetness because we expect instead to see behaviour showing "the more the better". However, this decline in response on either side of the learned value is a general feature of acquired sensory control of behaviour, called by psychologists of animal learning "the intradimensional stimulus generalization decrement".

Consider a response that has been learned to a stimulus on a particular dimension (such as a taste or a colour) at a particular value (slightly sweet or bright red). If a test value is presented that is substantially different from the trained value, the response is liable to be less strong: it will not generalize well to that test stimulus. The less the test value is like the learned value, whether higher or lower on that dimension, the weaker the response will be. The response may fail to generalize at all to a much lower or much higher value on that dimension: that would be a complete generalization decrement. Values closer to the learned stimulus value result in only a partial decrement: the preference or the aversion is only somewhat reduced.

In other words, the effect of a stimulus on a response should be proportional to the perceptible difference between the test level and the learned level. Recognition of some aspect of a food (or indeed of an eating situation) as being at the preferred level can be regarded as an inability of the preference response to discriminate between those two levels.

The limit of discrimination between two levels of a stimulus is known in psychology as the "just noticeable difference" (JND) or the difference threshold (Torgerson, 1958). This is a measure of the strength of influence of an input over an output, however, for any process in any sort of system. There can be JNDs of stimuli affecting ratings of intensity or liking, preference measured as relative intakes, or neural activity in a sensory fibre or brain region. Furthermore, the JND is independent of the experimenter's units of measurement, unlike measures such as stimulus–response slope, discrimination errors or tuning bandwidth.

People's preferences for tastes, smells and textures in familiar foods and drinks do indeed decline on either side of the personally ideal level in proportion to the JND in the test circumstances (Fig. 1.2; Booth, Thompson and Shahedian, 1983; Conner and Booth, 1992). Since the principle applies to visceral or external influences as well dietary ones, this measure of the strength of an influence on ingestive behaviour (and on ratings predictive of eating or drinking) has been called the "appetite triangle" (Booth, 1986). It represents the actual mechanism underlying the inverted U of the hedonic curves that are generated by averaging data across subjects, not plotting stimulus levels in JNDs and (as we shall see below) testing in unnatural situations.

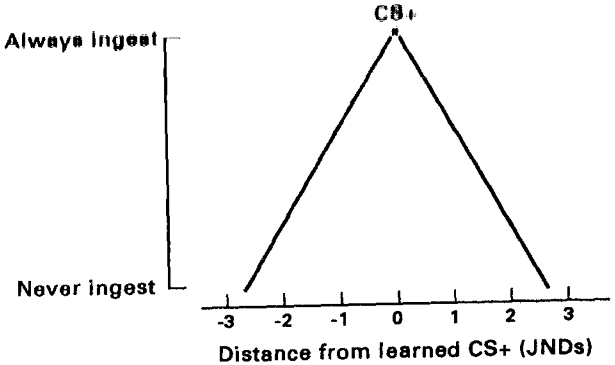

FIG. 1.2. Decline in recognizability and preference with distance in JNDs of the test item or situation above or below the value of its learned form. This function becomes a straight line when the slope of the descending limb is multiplied by − 1.

This principle for measuring causal strength can be turned on its head to provide a technique for identifying the exact nature of an influence controlling a response. What the investigator initially assumes is the adequate stimulus may only approximate to the pattern on which the brain is actually working. If we can find a more accurate specification of the effective stimulus, then it will give a smaller JND. In other words, the intake, the rating or the neuronal firing rate will show sharper acuity. The stimulus measure to which the response is consistently most sensitive is thereby identified as the best candidate for being the actual source of influence (Kendal-Reed and Booth, 1992).

Such a search for the most effective stimulus can be used to help identify sensory receptor agonists. It can also specify a neural channel to which learned synaptic changes have tuned a pattern of stimulation to a set of diverse receptors, e.g. from a recognized food item or a whole situation motivating ingestion.

1.3.3. Multiple controls of normal ingestion

This approach also provides the means to identify how different pattern-signalling channels interact during the recognition of a multi-feature object, such as the mixture of foods suited to current bodily need and external situation. The pattern-combination rule that gives the lowest JND is the best candidate from

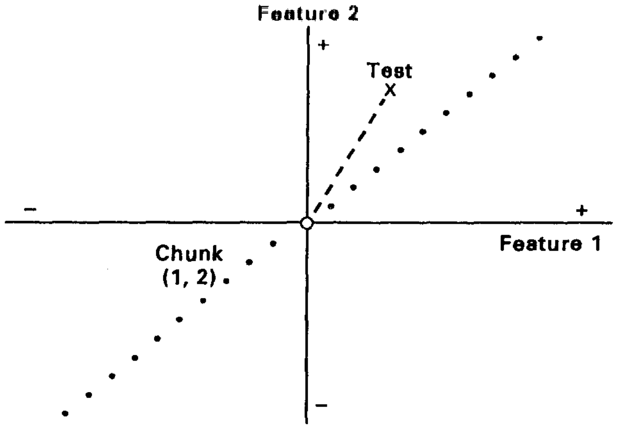

FIG. 1.3. Two simple or complex features of an object or situation that can vary in values independently of each other. Origin: The normal values of the two features. X: test version.

that evidence for the actual form of the interaction among effects within the brain.

Signals over the same channel will add together in JND units. Different channels, however, are orthogonal: they form dimensions at right angles to each other. Recognition and preference therefore decline with the multidimensional distance of the test stimulus from the learned configuration (Fig. 1.3). This distance is the square root of the sum of the squares of the JND-scaled distances in each of the dimensions entering the decision to ingest (or not). Hence, the salient influences on ingestion may interact non-additively.

Furthermore, separate patterns can become one by a learning process of unreinforced association or "chunking" (Wickelgren, 1979). Two or more features, consistently present at particular levels in a learned food or eating situation, can emerge in overall appetite as a single integral dimension (the diagonal in Fig. 1.3). The learned response will decline as the strength of the unitary combination rises or falls from the learned value and as the features' strengths depart from their learned proportions (as in the test stimulus in Fig. 1.3).

For example, for some people a savoury taste of greater or less intensity than preferred in a vegetable- or meat-based food emerges from mixtures of sweetener, salt, acid and bitter in proportions that mimic the complex taste pattern of monosodium glutamate (Fig. 1.4; Booth, Freeman and Lähteenmäki, 1991). The overall taste is unique but nonetheless, for this person, it is no more than the JND-scaled Euclidean combination of other patterns of gustatory stimulation: there is no need to invoke another type of receptor. The salty tastes of sodium chloride and monosodium glutamate, on the other hand, add together in JND units and so presumably result from action on the same sorts of sodium receptors.

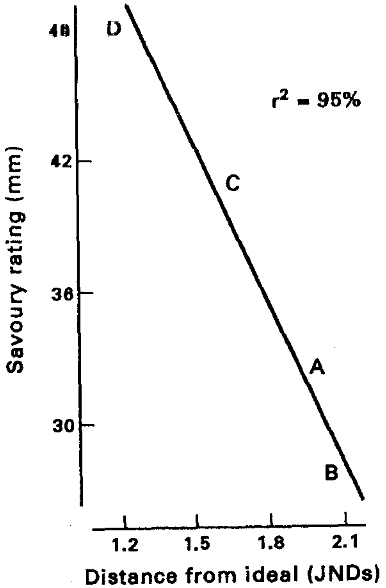

FIG. 1.4. Multidimensional JND-scaled distances of four mixtures of sucrose, sodium chloride, citric acid and caffeine from their ideal levels for an individual, plotted against the difference from ideal "savoury" taste (50 mm) rated by that person on tasting a sample of each mixture in chicken soup.

Multidimensional discrimination analysis also provides a quantitative account of tests on poor-quality foods or in unusual visceral states or external situations. The distance of the conditions of testing from what the human being or other animal expects of these features will put an upper limit on the disposition to ingest. This defect will combine according to Pythagoras's Theorem with whatever is being experimentally varied within the animal's range of recognition. This results in a low and rounded but still mathematically determinate peak to the appetite triangle (Fig. 1.5). Tuning sensitivity can therefore still be measured in situations that are difficult to control completely, so long as they do not depart too far from what the organism knows well.

To sum up then, a person, monkey or rat faced with a familiar diet in a recognizable internal state and normal surroundings will respond according to the distance of the combination of salient features in the whole situation from a situation for which a response has been learned. If the response is sufficiently facilitatory, the animal will eat or drink. If it is not, or there is active inhibition, the animal will not ingest.

What the individual ingests will depend on the relative contributions of the sensory qualities of the different foodstuffs present to overall facilitation. This

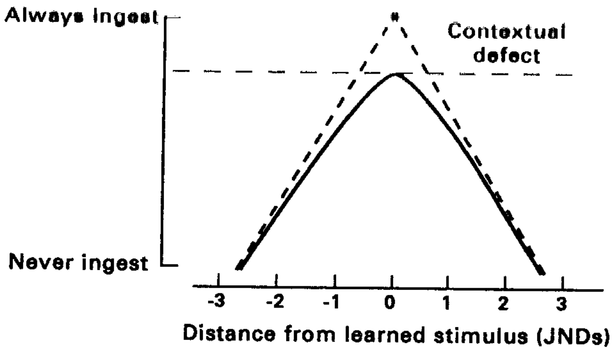

FIG. 1.5. Preference (or difference from familiar) for test samples varying in a simple or complex feature and having a constant defect (also uni- or multidimensional). When the distance of the varied feature from the learned level is sufficiently greater than the defect, this function approximates to the isosceles triangle of Fig. 1.2.

immediate food-generated facilitation is generally called *preference*. The preference for a food might be called its *palatability* if sensory preference is assumed not to depend on circumstances, but that is not generally true. Whether the individual ingests may also depends on visceral facilitation: this effect is often called "hunger" but that term has a wider sense of appetite for food (as opposed to "thirst" which is water appetite), whether facilitated internally or externally. Ingestion is also contingent on factors such as risk of predation in small mammals, the cost of effort (or, in people, of money) and social context (e.g. which other conspecifics are eating). This is sometimes called the *appropriateness* of the occasion, but that may also include the goodness of match of a food to other items on the menu and even to bodily state.

1.3.4. Control of ingestion by its after-effects

When ingestive inhibition arises from the effects of recent eating, this is known as a state of *satiety*. Satiating effects do not all arise from postingestional actions of food and drink, such as stretch of the stomach, chemical stimulation of the upper intestine or hepatic metabolism. Eating may stop because a prefilled plate is empty. Drinking may end because the contents of the cup or can are finished. The eater may simply have had enough of the taste of a food for a while, independently of how full the gut is.

Repeated exposure to a stimulus pattern causes the initial orienting, ingestive or defensive response to habituate. The response recovers after some minutes. Also, the introduction of a new stimulus (variety) can still excite the response, at least until continued presentation induces habituation to that stimulus also. When series of presentations are repeated, the habituation becomes faster. This shows that some residual memory of the previously habituated stimulus remains

and is called long term habituation. It may be one of several mechanisms in food specific satiation. Satiation that arises from habituation rather than from learning about the after effects of food consumption cannot contribute to regulation of energy balance through control of amount eaten.

Unvarying conditioned aversions and preferences cannot adjust the amount consumed to its caloric yield either, because these effects operate from the start of the meal, independently of how much is eaten.

The learned control of meal size on a particular food will be related to caloric yield only if an aversion (or at the least a lack of preference) can be confined to the end of a meal and controlled by how much energy has been ingested as well as by the food's sensory characteristics. Thus, calorically regulatory satiation at a meal requires a loss of ingestive facilitation that is specific both to a food and to a level of gastrointestinal repletion that have together been followed by an overabundance of dietary energy (Booth, 1972b; Booth and Davis, 1973; Gibson and Booth, 1989).

Besides this inhibitory learning, many natural associates of eating condition facilitation to stimulus combinations that predict them. These include postingestional effects of carbohydrate, fat and alcohol, perhaps the fuel they provide to the liver (Booth, 1972a). Other nutrients such as the essential amino acids from dietary protein can have the same ingestion-facilitating effects. All these nutrients can condition preferences to simple or complex food tastes, aromas, tactile textures and visual appearances. They also condition ingestion to combinations of food characteristics and bodily states, such as a full or empty gut (Booth and Davis, 1973; Gibson and Booth, 1979) or an incipient lack of essential amino acids (Gibson and Booth, 1986a; Booth and Baker, 1990). These provide qualitative (categorical) examples of the two-dimensional integration represented quantitatively in Fig. 1.3. Such mechanisms help to improve the match between nutrient requirements and food selection and intakes, although they do not provide upper limits on the intake of appetizing foods in hungrifying states.

Social and/or emotional associates also associatively condition appetite or its reduction. Novel foods given to young children with some praise become more attractive (Birch, 1990). Conversely, rewarding the eating of a food with a liked food reduces preference for the first food (Birch, 1990). External signals can also be conditioned to elicit eating (Weingarten, 1984). Thus, the social situations or emotional states that reinforce ingestion could conceivably also become parts of the learned complexes of stimuli for ingestive appetite. This would be a mechanism for emotional eating which could override learned visceral control of preferences and satiety.

1.4. Neurophysiologically oriented ingestive neuroscience

The work represented in this book is relevant to any research into neural mechanisms of ingestion, even if electrical recordings are not being made. Studies of intake and the brain should be designed to relate to what is known from integrative neurophysiology, as well as being sensorially and viscerally contextualized. A few examples are now outlined of such combinations of behavioural analysis, somatic control and neurophysiological ideas in the study of the central pathways of ingestion by other methods (Booth, 1990).

1.4.1. Are there centres for appetite and satiety?

Before the rise of cellular neurophysiology, the main approach in what was called physiological psychology was to analyse the behavioural consequences of destroying certain regions of the brain; this approach is now named neuropsychology. Lesions of the ventromedial region of the hypothalamus (VMH) made rats overeat and get very fat, while lesions in the far lateral hypothalamus (LH) stopped eating altogether or at least for some weeks. So a dual-centre theory of hunger and satiety was proposed, that the LH was the location at which feeding was organized and the VMH was the satiety centre. This idea seemed to be strongly supported by evidence that electrical stimulation of the LH could trigger eating and VMH stimulation could stop it, while activity recorded through large electrodes in the LH and VMH varied reciprocally in food-deprived and fed rats.

A similar pattern of evidence was the basis for proposing initially that the medulla contained dual centres for breathing in and breathing out. However, such a convergence of effects of lesions, stimulation and recording does not establish the location of an organizing centre, let alone its existence. For example, there might well be no more than efferent axons in such a region (Booth, 1968b). It was soon shown that the supposed medullary "centres" are indeed largely efferent pathways and expiration and inspiration are organized in complex networks extending through the pons into the midbrain (Porter, 1970). There has long been evidence for the importance of extrahypothalamic mechanisms in food intake. The other chapters in this book illustrate recent findings of that sort.

In any case, the postulation of a centre (even if it were confirmed to exist) would do nothing to explain either the neural mechanisms or the behavioural processes by which the function is achieved. It just transfers the "black box" from a boundary around the brain or body to a name for a place inside the brain. This strategy was called phrenology in the nineteenth century: it is no less fallacious if based on drug action or electrical recordings instead of on the effects of lesions (Booth, 1976). Scientific advance in integrative neuroscience requires the coordination of neurophysiology and microanatomy into a theory of neuronal networks that could perform a function such as organizing ingestive behaviour (Rolls, 1976, and in the final chapter of this book).

By the early 1970s, further analysis of effects of manipulating either the LH or the VMH had completely refuted the dual-centre theory of hunger and its satiety (Rabin, 1972; Ungerstedt, 1971). Yet this situation has still not permeated through to textbooks nor to some other areas of research in neuroscience. A selection of contrary evidence is now summarized. These are not neurophysiological data but they serve to illustrate how the above integrative behavioural framework can be used to approach the subsequent chapters that do centre on electrical recording and other evidence of cellular interconnections.

1.4.2. Hypothalamic synaptic fields in eating control

The first evidence against a lateral hypothalamic hunger centre came from improved anatomical specification of the elicitation of eating in the sated rat by injection of noradrenaline into the hypothalamus (Booth, 1967, 1968a). The microcannulae developed have not been improved on but they cannot imply a site of action with a precision of more than about 0.2 mm. Nevertheless, the noradrenaline feeding site was clearly the best part of a millimetre anterior to the lateral hypothalamic sites at which electrical stimulation was most likely to elicit eating, at the level where lesions most reliably caused aphagia (Booth, 1967).

Subsequent work focusing on the most effective region for adrenergic elicitation of eating identified a small area in or just lateral to the paraventricular nucleus, which is well rostral and somewhat medial to the LH (Liebowitz, 1978; Matthews, Booth and Stolerman, 1978). Rolls (1976 and this volume) found eating-related units in the lateral hypothalamus of monkeys but also more dorsal in the substantia innominata.

1.4.3. Ventromedial hypothalamic obesity

Experimental lesions of the hypothalamus (and tumours there) alter the autonomic balance at the stomach, endocrine pancreas, liver and white and brown fat, shifting defended body weight and sometimes altering eating in the process. Lesions in the ventromedial hypothalamic area immediately release gastric emptying from inhibition that it is normally under, especially during the rat's inactive period in the first part of daylight (Duggan and Booth, 1986, 1991). The resulting faster digestion and absorption stimulates extra insulin secretion and fat deposition, sufficiently to increase food intake on a palatable diet, but in any case making the rat more and more obese until feedback on satiety from the fat stores turns the dynamic phase into an asymptotic static phase of obesity (Toates and Booth, 1974). The continuous rapid absorption caused by the accelerated stomach soon adapts the autonomic balance and transmitter sensitivities on the pancreatic beta cell (if the ventromedial hypothalamic lesion has not already shifted the balance) and even more insulin is released, producing still more fat deposition (Campfield, Smith and Fung, 1982).

These changes are allied with normal central mechanisms controlling eating behaviour and its responsiveness to visceral signals. There are no defects in postingestional satiety mechanisms in rats with ventromedial hypothalamic lesions (Booth, Toates and Platt, 1976; Duggan and Booth, 1986). So the ventromedial nucleus and its surrounding hypothalamic region cannot be serving as a satiety centre. The effects of signals from the stomach and from circulating substances recorded in the VMH nucleus presumably act on neuroendocrine and autonomic outflows. Any effect on visceral inhibition of eating is generated secondarily in the periphery. For example, rapid gastric emptying will end nutrient absorption early, prematurely removing stimulation from intestinal chemoreceptors (Welch, Sepple and Read, 1988) and so releasing frequent meals (Booth, 1978).

1.4.4. Behavioural analysis of adrenergic eating

The brain organizes particular externally observable processes that operate over time periods from tens of milliseconds to seconds at the most. Thus, little of the information needed to build a neuroscience of ingestion can be extracted from measures of the accumulated consequences of much changing ingestive behaviour, like the amount eaten or drunk in 30 minutes or in a meal. This chapter therefore introduces forms of behavioural analysis that deal with time periods short enough for input/output relations not to change. The data can then be related to neural processes specified by electrical recording from single cells.

The adrenergic eating effect from the rostral hypothalamus has been approached this way. Since it was discovered that infusion of noradrenaline into the sensitive region would increase the size of an ongoing meal (Ritter and Epstein, 1975), as well as elicit eating, it has been thought that the effect was disruption of satiety. Behavioural analysis provided clear evidence against an increase in learned or unlearned sensory preferences (Matthews, Gibson and Booth, 1985) or indeed a decrease in aversiveness of the test diet (Sclafani and Toris, 1981).

Nevertheless, an injection evoking ingestion of sweetened condensed milk from rats sated half an hour previously did not elicit milk ingestion immediately after gastric intubation of the amount that the rats consumed after the usual presatiation procedure (Gibson and Booth, 1986b). This showed that the behavioural effect of noradrenaline did not depend on the blockade of all satiating influences, certainly not of strong postingestional satieties.

The only satiety effect found to be overcome by the injection was conditioned satiation, the learned decrease in flavour preference when the stomach was partly full (Matthews *et al.*, 1985; Booth, Gibson and Baker, 1987). The control of ingestion by the learned combination of dietary and visceral stimuli can be rather strong (Booth, 1985). Nevertheless, it requires complex processes of crossmodal integration with memory. Therefore, it is liable to be susceptible to cognitively disrupting factors such as excessive arousal. The noradrenergic synapses on which the injection acts are a local projection of the ascending reticular arousal systems. One may therefore wonder whether this is one of the neural mechanisms involved in emotional overeating.

1.5. The structure of this book

Research progress can only be made by focusing on technically answerable questions. This often requires specialization. Neurophysiological investigations of ingestive behaviour or the mechanisms controlling food or water intakes have generally focused on a particular category of afferent information and on the efferent modulation over which those inputs are predominant.

A book has to be a sequence of chapters. Yet we have seen that ingestion is controlled by conjunctions of afferent activities rather than by a sequence of signal onsets or offsets. Similarly, the movements of the mouthparts and of food handling during ingestion are largely co-temporaneous, even though obviously there are also sequences of approach and consumption and cycles of biting, chewing and swallowing.

To emphasize, therefore, the visceral context within which any ingestion or refusal of food or drink takes place, the first four specialized chapters deal with the intake-related neurophysiology of the liver, intestine and stomach. Then we consider the tactile control of the movements of the jaw and tongue that are involved in all eating and drinking. Next come two of the other oral senses, taste and smell (which is retronasal for the aroma of food in the mouth as well as orthonasal for sniffed food odours). Finally, we consider examples of crossmodal integration between the appearance, taste and smell of a food and the neural systems transforming recognition of a food into action towards it.

The authors have been encouraged to illustrate their chapters by neurophysiological findings from their own laboratories while providing a brief overview of that aspect of the neurophysiology of ingestion for the non-expert. There is not the space nor perhaps are we yet at the time to bring out the connections and the gaps between the different lines of research. This is the first collection of reviews for a wide readership that covers virtually the whole range of neurophysiological approaches to ingestive behaviour in mammals. As such it can serve as something of a landmark in research activity within behavioural neuroscience as well as an introduction for newcomers to this intriguing topic for investigation.

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