1

Introduction to Neuroimaging and the Brain–Stomatognathic Axis

1.1 Why Do Dentists Need to Understand the Brain?

1.1.1 Introduction

If we look into any textbook of clinical dentistry – be it oral pathology, prosthodontics, periodontics or orthodontics – we may not feel surprised that the word 'brain' would appear just very few times in the whole book. Traditionally, dentists are trained as an expert in treating oral diseases and the topics related to the brain, and its relevant disorders are usually categorized as systemic issues. The dichotomy of 'dental vs. systemic' suggests that the brain and behaviour issues are beyond the spotlight of dentists. Such alienation is even pronounced if we hold a 'pathological perspective' on the association between the brain and dentistry: oral diseases are usually not the primary aetiology of neurological/mental disorders, cardiovascular, gastrointestinal or endocrinal diseases (Figure 1.1). Therefore, there is no urgent need for dentists to learn the knowledge of the human brain.

However, the association between the brain and dentistry may show a different story if we adopt a 'functional perspective'. Here, the brain, behaviour and oral health are directly linked if we consider that the brain plays a crucial role in maintaining oral functions, and the integrity of mental functions is critical to maintaining oral health. If we adopt the view that the brain and mental functions guided by the brain are essential to all human behaviours (e.g. from eating to toothbrushing), we may find that the brain has an essential and more dominant role in oral health (Figure 1.1).

In the following sections, we elaborate on this functional perspective by revisiting three lines of evidence. Historically, we see that dentistry and brain science are the 'old alliance' for more than 100 years. Educationally, we discuss the role of neuroscience in the curriculum of dental education. Finally, the new engagement between dentistry and the brain via neuroimaging methods is highlighted.

1.1.2 The 'Old Alliance' Between Dentistry and Brain Science

The first evidence of the alliance between dentistry and brain science exists in an article published 130 years ago entitled *Reflex Neurosis in Relation to Dental Pathology*. The author mentioned that '. . . pain in a tooth is not indicative of the source of trouble, . . . The cause may be remote or in another tooth' (Hayes 1889), a phenomenon now we may consider as heterotopic

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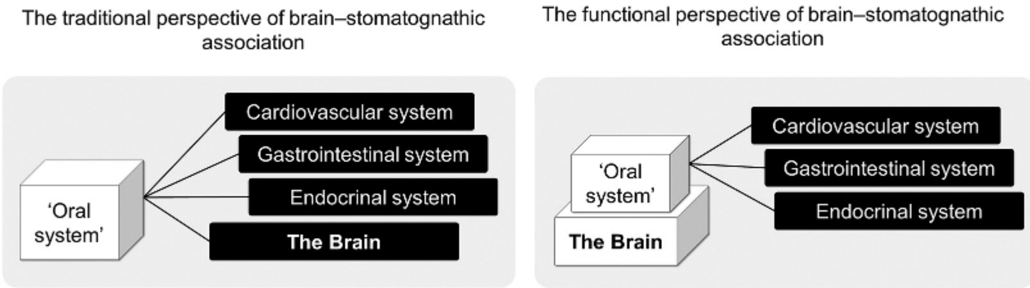

Figure 1.1 The association between the brain and the stomatognathic system. The traditional perspective highlights the brain as a 'systemic factor' associated with oral health, just like the factors related to other body systems. The functional perspective highlights that the brain and mental functions guided by the brain play an essential role in stomatognathic functions.

pain. Subsequently, the author put forward some insightful speculation on orofacial pain:

> Cerebral diseases, for example, insanity, softening of the brain, tumors and inflammation may produce odontalgia, but clinical reports reveal comparatively few, inasmuch owing to their obscurity positive diagnosis is often rendered difficult (Hayes 1889).

Though not scientifically accurate from the modern view, the statement points out the complex association between the brain and orofacial pain, which has confused dentists for more than one century. The alliance becomes cemented due to the challenge of treating orofacial pain, and new technologies, including neuroimaging, have provided new insights into this field (see Chapter 6). Our second evidence comes from the issues of infection control, especially the brain abscess secondary to dental infection. At present, dentists have been highly aware of infection control within the oral cavity. However, new challenges have emerged, such as the recent debates on the neuroinflammatory mechanisms that may underlie the link between neurodegenerative disorders and periodontal diseases (see Chapter 7). Finally, the third evidence of the old alliance has an even longer history. Back in 1790, when the terms 'brain science' and 'dentistry' have not yet popularized, in an article entitled '*Pathological Observations on the Brain*', the author reported a potential association between epileptic signs and symptoms and irregular behaviour in eating and drinking (Anderson 1790). The finding echoes the link between the brain and oral sensorimotor functions, extensively studied in animal research (Lund 1991). New issues have emerged in modern days. For example, can older individuals be benefited from oral functional training to improve mastication and swallowing (Sessle 2019)? Can patients with neurodegenerative disorders, who have deficits in mental functions, also improve their oral functions? There are more challenges to meet for the old alliance between dentistry and brain science.

1.1.3 Dental Education: The Role of Neuroscience and the Brain

In the previous section, we have briefly discussed how the research of the brain has been linked to issues of oral health. However, the discussion may not be complete without looking into dental education for the following questions: has the role of brain science been recognized in dental education?

1.1.3.1 The Tradition of 'Dentists as Surgeons'

A discussion of early dental education will not be complete without mentioning the contribution from Pierre Fauchard, widely recognized as the Father of Modern Dentistry, with the first textbook of dentistry *Le Chirurgien Dentiste* ('*The Surgeon Dentist*') published in 1728. As the name suggests, dentistry is the discipline of managing dental diseases with a surgeon's training. Notably, in this book, Fauchard has extended the professional domain of dentists from 'teeth' to the oral cavity (including the soft tissue). The new profession, a 'surgeon dentist', is different from a 'toothpuller' in the seventeenth to eighteenth centuries (Lynch et al. 2006). Though he also emphasized the relationship between oral and systemic diseases (Lynch et al. 2006), the primary task for dentists is to fix the structural deficits of the oral cavity, such as restoring a decayed tooth or replacing the missing teeth with a denture. All the jobs require dentists to be capable of performing complicated surgical skills.

An over-focus on the surgical skills of dental treatment, however, had gradually received criticism since the early days when dental education became an independent discipline. As pointed by Eugene Talbot early in 1900:

> The result is that study of the general diseases which affect the mouth, jaws and teeth have been neglected. Limitations of a dental education have prevented the dentist from associating local diseases with systemic causes (Talbot 1900).

The statement corresponds to the degree delivered for this new profession, namely Doctor of Dental Surgery (DDS), at Talbot's time. He further showed the concern that '. . . the graduate of dental surgery is not competent to associate systemic diseases with their effects on the teeth, nor is he capable of appreciating systemic lesions due to overtreatment of pathologic conditions of the teeth' (Talbot 1900). The gap between a dentist and medical knowledge would make dentists ignore the systemic condition of patients – moreover, the ignorance may further exacerbate systemic health when dentists 'overtreat' patients (Talbot 1900).

1.1.3.2 Brain and Neuroscience: Is It Neglected in Dental School?

According to the Basic Science Survey Series of the American Dental Education Association (ADEA), neuroscience is widely taught in most dental schools in North American. In 2014, among 66 dental schools, 31 (47%) offered neuroscience as a standalone course, with the others integrated the neuroscience topics into other courses (Gould et al. 2014). It is also noteworthy that in most dental schools, the course was delivered by teachers from medical schools, who may not tailor-make the course for dental students (Gould et al. 2014). The average year of teaching of the teachers is relatively high (23.1 years), suggesting fewer younger teachers are involved in the field (Gould et al. 2014). Critically, the topics to be delivered significantly varied between courses. Some topics, such as the knowledge of cranial nerves, were taught averagely for three hours. In contrast, issues of the neuropathic mechanisms of pain, including nerve regeneration, neuralgia, allodynia and hyperalgesia, were taught less than half an hour (Gould et al. 2014). Topics related to the human brain were taught in most of the courses. Nevertheless, among the 31 independent neuroscience courses, almost half of them focused on neuroanatomy, which emphasizes the knowledge of brain structure rather than the link between the brain and oral functions. This alienation reflects that many courses were taught by personnel outside the dental schools and may not provide what dentists need to know for their clinical careers.

Therefore, for teaching neuroscience and brain science in dental schools, the real challenge is not the time and classes allocated for teaching, but how these materials are taught. Non-dental school faculties mainly taught the courses, and the topics were less tailored for dentistry. For example, in some syllabi of the neuroscience courses, the issue 'pain' is taught alongside somatosensation. Nowadays, we have much evidence showing that pain, as a more generalized cognitive–affective experience, is associated with the brain mechanisms of attention, emotional and cognitive processing (see Chapter 6). In this case, a focus on the brain and mental functions, such as the modulatory effect of attention and cognitive appraisal on pain, should be tailored for dental students since it is highly associated with the clinical management of patients.

1.1.4 The 'New Engagement': Modern Cross-Disciplinary Research of Dentistry and Brain Science

Instead of being a comprehensive textbook on the neurobiology of dentistry, this book aims to outline the 'new engagement' between dentistry and brain science, with neuroimaging as a critical approach to bridge the two fields. Here, we discuss the trend of cross-disciplinary research between dentistry and brain science, according to two brief bibliometric surveys. Firstly, a survey based on PubMed was performed by the keywords 'dental' and 'brain' and the search was limited to titles and abstracts of the literature (tooth[mesh] OR oral[mesh] OR dental[mesh] OR dentistry[mesh] OR teeth[tiab] OR to*oth[tiab] OR oral[tiab] OR dental[tiab] OR dentistry[tiab] AND brain[tiab]*). The findings revealed that by December 2020, 20261 research papers had been documented in PubMed. The number of publications shows a pronounced rise in recent years, which almost doubled within 10 years. For example, between 1980 and 1989, the number of publications $n = 1566$. This number rose from 1990 to 1999 ($n = 2684$) and almost doubled from 2000 to 2009 ($n = 4721$). From 2010 to 2019, the number doubled again to $n = 9331$. As discussed in Section 1.2, the increasing number of publications on the brain topic corresponds to the increasing number of publications on neuroimaging, which has become a pivotal method in studying the human brain.

A second survey was conducted by searching for the past and current research projects funded by the National Institutes of Health (NIH), USA, using the online platform of Research Portfolio Online Reporting Tools (RePORT) report. From 2020 to February 2021, the keywords 'dental' and 'brain' have led to 106 projects, with 39 projects funded by the National Institute of Dental and Craniofacial Research (NIDCR). This number is almost twice the number of sponsored projects (53) in the whole 1990s when the NIDCR funded 29 projects. The results suggest an increasing trend of cross-disciplinary research between oral and brain sciences. Critically, not all the projects were granted by the NIDCR, which specializes in orofacial medicine. Several projects were supported by the National Institute of Mental Health and the National Institute on Aging, highlighting the importance of oral issues in cognitive deficits and aging.

1.1.5 Summary

- From a functional perspective, the brain, behaviour and oral health are directly linked because the brain plays a crucial role in maintaining oral functions, and the integrity of mental functions is critical to maintaining oral health.
- The alliance between the research on dentistry and the brain has a long history. It contributes to tackling unsolved challenges (e.g. orofacial pain) and new challenges (e.g. aging and oral functions).
- Topics of neuroscience and the brain are not neglected in dental education. However, many courses are taught by non-dental school faculties, and the topics were less tailored for dentistry.
- Recently, cross-disciplinary research on oral and brain sciences has quickly emerged in the number of publications and research grants.

1.2 What Is Neuroimaging?

1.2.1 Introduction

In Section 1.1, we have highlighted a significant overlap between dentistry and brain science. Though the two fields are closely linked from a functional perspective, there exists a vast difference between research approaches of the oral cavity and those of the brain. Dentists can visually examine the oral structure, and oral functions can be quantified with a chairside set of assessments. In contrast, brain functions and mental status, sometimes metaphorized as a 'black box', can hardly be examined directly at the chairside. Therefore, a pivotal step to facilitate the investigation of the brain is to develop the technology for quantifying brain structure and functions. Neuroimaging, defined as a non-invasive approach of 'visualizing the central nervous system, especially the brain, by various imaging modalities' (MeSH 2012), is such a technological breakthrough that revolutionizes the research approaches of the brain.

A common myth is that neuroimaging or 'brain scan' would be a kind of 'modern magic'. The impression is strengthened by some sci-fi movies, where 'peeking into the brain' is taken as an icon of something futuristic. Contrary to the popular myth, the term 'neuroimaging' has been adopted as a common method for regular clinical investigation and research. In the following sections, we outline the primary methods of neuroimaging approaches in brain science, and their roles in brain science and practical implications in dentistry are highlighted.

1.2.2 What Is the Role of Neuroimaging Research in Dentistry

1.2.2.1 Trends of Research Publications in Dental Neuroimaging Research

Table 1.1 summarizes the number of dental research publications combined with research on the brain and neuroimaging, according to a PubMed-based survey. The trend of publication of dental research related to neuroimaging was strikingly similar to that related to the brain. Before 1970, only a few publications were found in these fields. In contrast, after the 1990s, the percentage of these studies showed a pronounced increase. Notably, this trend in publication can be compared with the dental research related to neuroscience in general, as recently reported by Iwata and Sessle (2019). In terms of brain and neuroimaging research, almost half of the dental research on brain and neuroimaging was published last decade (2011–2020) (Table 1.1). This trend is very different from the general field of neuroscience. It

Table 1.1 Trends of the academic publication[a] in dental research related to brain and neuroimaging.

	Dentistry + Brain		Dentistry + Neuroimaging	
Period	**No. of articles**	**Percentage**	**No. of articles**	**Percentage**
2011–2020	10004	49	391	65
2001–2010	5119	25	152	25
1991–2000	2773	14	61	10
1981–1990	1719	8	2	0
1971–1980	631	3	0	0
1961–1970	145	1	0	0
1951–1960	53	0	0	0
before 1951	11	0	0	0

[a] The number of articles was surveyed using PubMed with the following combination of keywords: 'tooth[mesh] OR oral[mesh] OR dental[mesh] OR dentistry[mesh] OR teeth[tiab] OR tooth[tiab] OR oral[tiab] OR dental[tiab] OR dentistry[tiab]' in conjunction with 'brain[tiab]' and 'neuroimaging[tiab]' for 'Dentistry + Brain' and 'Dentistry + Neuroimaging', respectively.

is also noteworthy that more than 90% of the dental research on neuroimaging was published after the mid-1990s, about the same time when functional magnetic resonance imaging (fMRI) came into practice (Bandettini 2012). The trend reflects that technological innovation of biomedical imaging may facilitate cross-disciplinary research on dentistry and the brain.

1.2.2.2 The 'Landmark Discoveries or Concepts': Past and Future

In their article '*The Evolution of Neuroscience as a Research Field Relevant to Dentistry*' for the Journal of Dental Research (JDR) Centennial Series, Iwata and Sessle enlisted several achievements of orofacial neuroscience in the decades (Iwata and Sessle 2019). Many of these achievements have been made based on clinical, animal and laboratory research. For example, the gate control theory has been widely investigated from the clinical to the molecular levels. Remarkably, animal research has unravelled a complex pattern of bi-directional projections between the stomatognathic system to the brain (Figure 1.2). Investigation of the human brain may disclose more insights on this topic. While the 'gating' mechanism at the spinal level has been gradually elucidated, how the nociceptive processing is translated to pain, a subjective experience, has remained a challenging issue. As noted in Chapter 6, neuroimaging methods may help extend our current knowledge in pain and its management. Another example is the investigation of neural mechanisms of mastication and swallowing, which significantly impact our understanding of oral physiology and the management of oral dysfunctions. Recent neuroimaging findings, on the one hand, confirm the evidence from animal research (e.g. the role of primary sensorimotor cortices in chewing) (Table 1.2 and Figure 1.2). On the other hand, neuroimaging findings disclose new knowledge about the role of learning and cognitive control in oral motor functions (Table 1.3). As shown in Table 1.2, many examples reveal how neuroimaging, as an exploratory tool, broadens the frontier of orofacial neuroscience into the uncharted area.

1.2.3 Methods of Neuroimaging

As an approach to visualize the central nervous system (CNS), neuroimaging consists of various methods to image the brain. The methods can be generally categorized by the degree of invasiveness, by the brain features to be quantified (e.g. brain structure or functions), and by the signals to be detected (e.g. neural activity or cerebral flow). A brief introduction of the methods is summarized in the following sections, and more detailed mechanisms are discussed in Chapter 2.

1.2.3.1 Invasive Methods of Neuroimaging

It would be contradictory to talk about an invasive imaging method if we strictly define neuroimaging as a non-invasive approach. However, some invasive approaches have provided crucial conceptual advancement in neuroimaging. For example, in electrocorticography (ECoG), experimenters detect brain signals using a meshwork that consists of multiple electrodes. This meshwork is overlaid on the dura of the brain, and therefore, the response of the electrodes at different positions can be (though roughly) mapped to the anatomical region of the brain (Gazzaniga et al. 2019). The method was limited to patients who received brain surgery. ECoG reveals the feasibility of brain mapping, i.e. to map the association between the geometric features of the brain and mental functions, a fundamental element of modern neuroimaging.

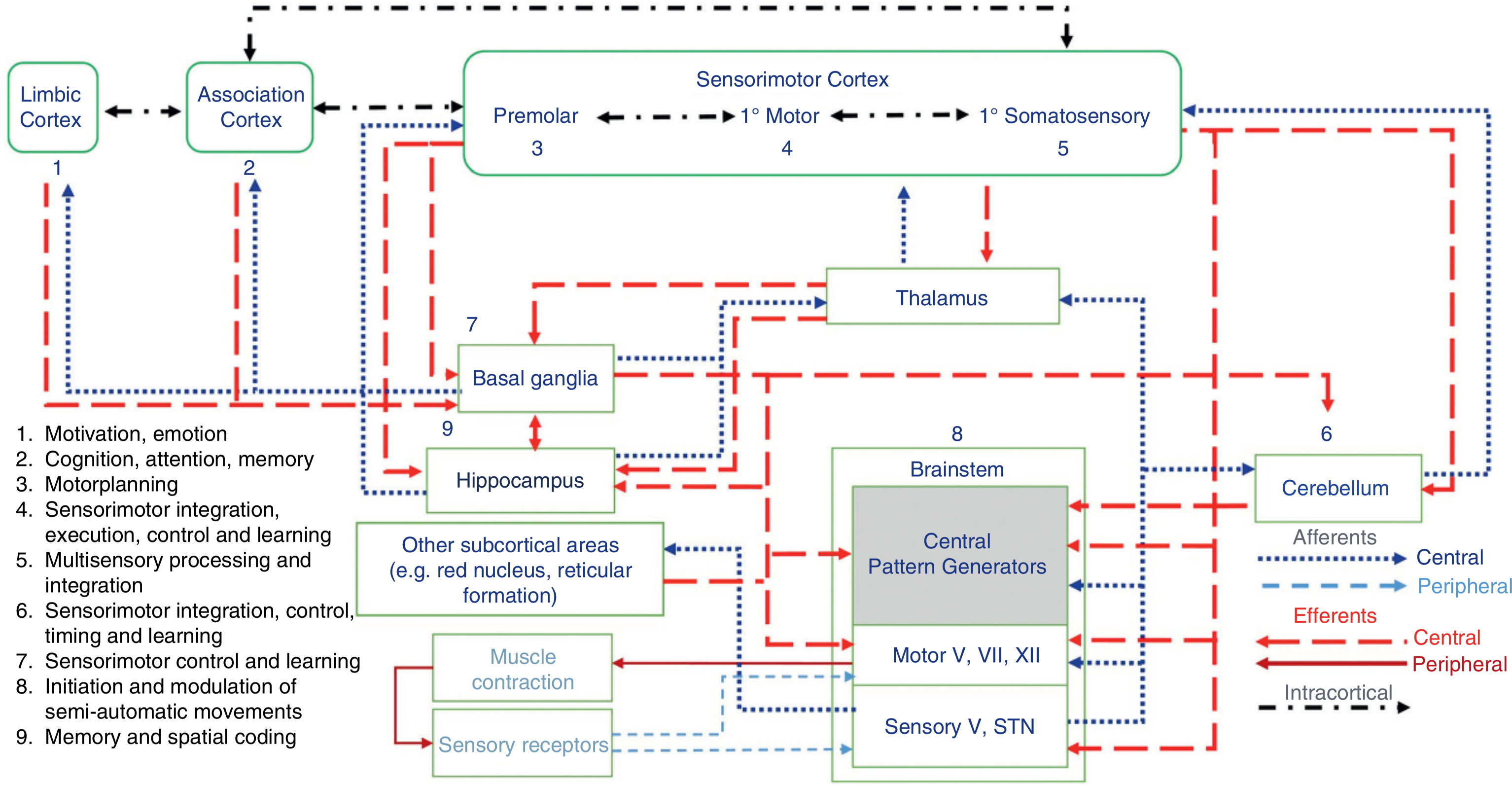

Figure 1.2 A general view of the neural circuitries of the brain mechanisms of orofacial functions. The circuitries between the central and peripheral sites (i.e. pathways labelled in blue and red) are investigated primarily via animal models. Notably, the circuitries within the brain (i.e. the intracortical pathways labelled in black) have not been fully elucidated. *Source:* Avivi-Arber and Sessle (2018). Reproduced with permission of John Wiley and Sons.

Table 1.2 Selected findings (since 2010)[a] of neuroimaging research, which are related to the issues of the 'landmark discoveries or concepts' of oral neuroscience (Iwata and Sessle 2019), as quoted in field (A) to (G).

Source	Participants	Methods	Major findings
(A) 'Presentation of the gate control theory of pain'			
Brügger et al. (2012)	Healthy adults	fMRI	'Cerebral toothache intensity coding on a group level can thus be attributed to specific subregions within the cortical pain network'.
Gustin et al. (2011)	TNP and TMD patients	sMRI, MRS	'. . .neuropathic pain conditions that result from peripheral injuries may be generated and/or maintained by structural changes in regions such as the thalamus'
(B) '. . . the multidimensionality and biopsychosocial aspects of pain and their application to improved diagnosis and management of orofacial pain conditions'			
Youssef et al. (2014)	Painful TN and TMD patients	ASL-MRI	'. . . non-neuropathic pain was associated with significant CBF increases in regions commonly associated with higher-order cognitive and emotional functions ...'
Weissman-Fogel et al. (2011)	Patients with nontraumatic TMD	fMRI	'. . . the slow behavioural responses in idiopathic TMD may be due to attenuated, slower and/or unsynchronized recruitment of attention/cognition processing areas'.
(C) 'Discovery of trigeminal nociceptive afferents and their modulation by processes within orofacial tissues . . .'/'Discovery of the plasticity of the nociceptive neurons . . .'			
Gustin et al. (2012)	Patients with painful TN and painful TMD	fMRI, ASL-MRI	'. . . while human patients with neuropathic pain displayed cortical reorganization and changes in somatosensory cortex activity, patients with non-neuropathic chronic pain did not'.
Moayedi et al. (2012)	TMD patients	DTI	'. . . novel evidence for CNV microstructural abnormalities that may be caused by increased nociceptive activity, accompanied by abnormalities along central WM pathways in TMD'.
(D) 'Discovery of nociceptive neurons in the brain and their modulation by intrinsic CNS circuits and endogenous mediators. . .'			
Desouza et al. (2013)	Patients with idiopathic trigeminal neuralgia	sMRI	'These findings may reflect increased nociceptive input to the brain, an impaired descending modulation system that does not adequately inhibit pain ...'
Abrahamsen et al. (2010)	TMD patients	fMRI	'. . . hypnotic hypoalgesia is associated with a pronounced suppression of cortical activity ...'
(E) 'Definition of the central pattern generators for chewing and swallowing'			
Lowell et al. (2012)	Healthy adults	fMRI	'The greater connectivity from the left hemisphere insula to brain regions within and across hemispheres suggests that the insula is a primary integrative region for volitional swallowing in humans'.
Quintero et al. (2013)	Healthy adults	fMRI	'. . . demonstrated that brain activation patterns may dynamically change over the course of chewing sequences'.
(F) '. . . discovery of the plasticity of sensorimotor cortex and other CNS regions in relation to orofacial sensorimotor control, learning and adaptation to injury and other changes in orofacial tissues'			
Kimoto et al. (2011)	Edentulous patients wearing a CD and an IOD	fMRI	'. . .differential neural activity in the frontal pole within the prefrontal cortex between the two prosthodontic therapies – mandibular CD and IOD'.
Luraschi et al. (2013)	Edentulous patients wearing a CD	fMRI	'Changes in brain activity occurred in the adaptation to replacement dentures ...'

Table 1.2 (Continued)

Source	Participants	Methods	Major findings
(G) 'Delineation of peripheral processes and CNS circuits underlying touch, temperature, taste and salivation, including the discovery of a fifth taste, umami'			
Trulsson et al. (2010)	Healthy adults	fMRI	'. . . PDLMs, and SA II-type receptors in general, may be involved in one aspect of the feeling of body ownership'.
Nakamura et al. (2011)	Healthy adults	fMRI	'The peaks of the activated areas in the middle insular cortex by umami were very close to another prototypical taste quality (salty)'.

ASL-MRI: arterial spin labelling magnetic resonance imaging; CBF: cerebral blood flow; CD: complete denture; CNV: the trigeminal nerve; DTI: diffusion tensor imaging; fMRI: functional magnetic resonance imaging; sMRI: structural magnetic resonance imaging; IOD: implant-supported denture; MRS: magnetic resonance spectroscopy; PDLM: periodontal ligament mechanoreceptor; SA: slowly adapting; TMD: temporomandibular disorders; TN: trigeminal neuropathy; TNP: trigeminal neuropathic pain; WM: white matter.

[a] The survey is performed using Google Scholar, with the date of publication ranged from 1 January 2010 to 30 May 2021.

Source: Field (A) to (G) based on Iwata and Sessle (2019).

Table 1.3 Selected findings (since 2010) of brain imaging research related to the clinical disciplines of dentistry[a].

Clinical topics[a]	Potential clinical implications	Source
Prosthodontic treatment	For edentulous patients, reduced prefrontal activation associated with tooth loss may be prevented by chewing with a denture.	Kamiya et al. (2016)
Prosthodontic treatment	The adaptation to replacement of dentures may be associated with changes in brain activity during oral motor tasks.	Luraschi et al. (2013)
Prosthodontic treatment	Adaptative chewing experience induced by palate coverage was associated with changes in brain activity associated with motor learning.	Inamochi et al. (2017)
Dental implant	In rats, tooth loss and installing dental implants may be associated with neuroplasticity at the facial somatosensory/motor region.	Avivi-Arber et al. (2015)
Dental implant	Osseoperception may be associated with the brain and the processing of primary and secondary somatosensory areas.	Habre-Hallage et al. (2012)
Orthodontic treatment	Functional appliances may work as exercise devices for neuromuscular changes associated with muscle adaptation and brain activation.	Ozdiler et al. (2019)
Orthodontic treatment	In rats, inflammation induced by tooth movement may relate to the activity of the somatosensory cortex and insula, which may be associated with higher sensitivity to pain.	Horinuki et al. (2015)
Occlusion	Occlusal discomfort may be associated with attention and/or self-regulation of the uncomfortable somatosensory experience.	Ono et al. (2015)
Occlusion	Regulation of occlusal force and periodontal sensation was modulated by prefrontal activity.	Kishimoto et al. (2019)
Periodontal treatment	In rats, mechanical and electrical stimuli may respectively excite activation at the primary and secondary somatosensory cortices.	Kaneko et al. (2017)
Periodontal and systemic health	Periodontal inflammatory/infectious burden is associated with the accumulation of amyloid-β plaques, a key feature of Alzheimer's disease.	Kamer et al. (2015)
Periodontal and systemic health	Poor periodontal health may be associated with lacunar infarction, a potential cause of dementia.	Taguchi et al. (2013)

[a] All the search was performed using PubMed, with date of publication ranged from 1 January 2010 to 31 May 2021.

1.2.3.2 Non-invasive Methods – Different Focuses of Brain Features

Neuroimaging in the modern days highlights a non-invasive procedure. For example, no surgical procedure is required for scanning the brain. However, for a non-surgical approach, subjects may still be exposed to ionizing radiation. The diverse methods can be broadly categorized according to what brain features to be assessed. Computed tomography (CT) and magnetic resonance imaging (MRI) primarily focus on imaging brain structure. As an application of X-ray imaging, CT may be the tool that dentists are primarily familiar with. It is advantageous in providing a good contrast on the bone tissue which is particularly useful for surgical procedures of dental treatment. In contrast, the MRI assesses the brain based on the water molecules (or strictly speaking, the hydrogen nuclei of the water molecules) in brain tissue. An MRI scanner detects the electromagnetic signals derived from the change of nuclear spinning of hydrogen nuclei. MRI can 'map' brain structure because the physical events can be affected by the density of protons (i.e. the hydrogen nuclei) and the relaxation processes associated with the biochemical features of brain tissue (e.g. containing less or more fat). Therefore, different anatomical features (e.g. fat-containing neural fibres and water-containing cerebrospinal fluid [CSF]) can be contrasted in MRI images. This advantage enables MRI the primary tool to investigate the morphology, including the size and shape, of the anatomical structure of the brain (Jenkinson and Chappell 2018). In contrast to the structure-oriented methods, functional approaches focus on detecting the neurophysiological or brain signals associated with mental functions. The approaches include electroencephalogram (EEG), magnetoencephalography (MEG), positron emission tomography (PET), and functional MRI (fMRI), as discussed below.

1.2.3.3 Non-invasive Methods – Different Sources of Brain Signals

In contrast to structural neuroimaging, functional neuroimaging focuses on the brain signals associated with mental functions. These function-focusing methods can be categorized into two broad domains. Firstly, EEG and MEG are the methods that directly assess the magneto-electrical signals from the brain. Both methods rely on the use of an array of strategically deployed sensors on the surface of one's head to collect weak magneto-electrical signals from the brain. Both methods focus on the magnetic/electrical events of neural activity associated with mental functions. Secondly, PET and fMRI are the methods that assess the metabolic events of the brain, which can be inferred as a surrogated index of neural activity (Gazzaniga et al. 2019). PET assesses the change in metabolic events associated with cerebral blood flow (CBF) by detecting the dynamics of the radioactive-labelled tracer injected into subjects. fMRI, in contrast, detects the change of the proportion between the oxygenated and deoxygenated haemoglobin as a metabolic index, which is indirectly associated with the change of neural activity (see Chapter 2). Notably, both methods focus on quantifying the relative change of brain signals between different conditions (e.g. when subjects perceive painful vs. non-painful stimuli). Therefore, the PET and MRI signals do not assess absolute metabolic activity and may not be interpreted as the actual level of neural activity (Gazzaniga et al. 2019).

1.2.4 Structural MRI Methods

Due to the widespread use of MRI in neuroimaging of the human brain, the following section focuses on the application of MRI in the investigation of both structural and functional issues of the brain. The primary goal of structural magnetic resonance imaging (sMRI) methods, in general, is to determine the size and shape of anatomical structures of the brain (Jenkinson and Chappell 2018). Various methods have been developed for investigating grey matter and white matter, two major regions of the CNS.

1.2.4.1 *T*1-Weighted Structural MRI

The most common sMRI data is acquired by *T*1-weighted imaging. Imaging is acquired by weighing on the '*T*1' value, which refers to the time constant for longitudinal relaxation, an index of the rate for protons to return to equilibrium. Critically, this value varies depending on the biochemical components of tissues: the fat-containing tissue (e.g. neural fibres of white matter) has a shorter *T*1 compared to the tissue less rich in fat (e.g. grey matter). In a *T*1-weighted image, the signals collected would preferably show a higher intensity (i.e. brighter) for brain tissue with a higher content of fat and lower intensity for tissue with a lower content of fat. Therefore, the spatial distribution of white matter and grey matter can be differentiated by image intensity. The greatest advantage of *T*1-weighted imaging is that it can be analyzed using different methods to disclose information on brain morphology. For example, tissue-specific segmentation is a method that separates grey matter, white matter and the space of CSF from the whole-brain image. Voxel-based morphometry (VBM) can be used to estimate the amount of grey matter and white matter within each voxel, which can be further used for a group-based comparison. The method has been widely used for clinical investigation, such as assessing the reduction in hippocampal grey matter between patients with Alzheimer's disease and healthy controls. In addition, the surface-based analysis is widely used to estimate the thickness of the cortical tissues and the volume of cortical and subcortical regions, which are critical structural features associated with clinical factors (see Section 2.3).

1.2.4.2 Diffusion MRI

While the *T*1-weighted image provides a spatial feature of different brain regions, it provides less information regarding how the brain forms a connectional network. The key to understanding the connection between brain regions is to estimate the orientation of neural fibres. Diffusion magnetic resonance imaging (dMRI) is an MRI method to estimate the distribution of the 'fibrous' space in the brain. The method is based on the phenomenon that water molecules spread less freely in the compartment abundant of axons because the freedom to spread is limited by the axons aligned in the same direction. In contrast, the molecules spread more freely in the fluid space, such as the ventricles, where less hindrance exists to restrict the direction of spreading. Diffusion tensor imaging (DTI) is developed to quantify the directionality of diffusion. There are two major applications of dMRI. Firstly, it helps to examine the microstructural properties of the white matter (Jenkinson and Chappell 2018). For example, fractional anisotropy (FA) is a widely used index related to axonal density, the myelination of nerve fibres, and the membrane permeability (Jones et al. 2013). Secondly, dMRI is useful for exploring the structural connectivity of the brain, i.e. how the brain is wired by neural fibres. At present, it is the only tool that can probe the structural connectivity of the human brain *in vivo* (Jenkinson and Chappell 2018). Tractography has been used to visualize the streamlines that pass between different brain regions. The results provide further information about how brain regions are wired to form a network (see Section 2.3).

1.2.5 Functional MRI Methods

The fMRI methods have two major applications. A task-based fMRI study investigates the brain signals associated with mental functions. Imaging is conducted when subjects are performing a behavioural task that induces the mental functions of research interest (see Section 2.2). A resting-state fMRI study investigates the intrinsic activity of the brain, i.e. the spontaneous activity when subjects are not perturbed by external stimuli (see Section 2.4). The fMRI methods can be further categorized according to the nature of the brain signals detected, as discussed below.

1.2.5.1 Blood-Oxygen-Level-Dependent fMRI

The blood-oxygen-level-dependent (BOLD) fMRI detects the changes in the proportion of deoxygenated and oxygenated haemoglobin in the brain. This metabolic event (i.e. oxygenation of haemoglobin) is further associated with neural activity. Firstly, the brain region with increased neural activity is associated with more energy consumption, i.e. for synaptic activity. Secondly, oxygen consumption is associated with increased CBF and changes in cerebral vessel volume, leading to an over-supply of the oxygenated vs. deoxygenated haemoglobin (see Section 2.2). Finally, deoxygenated haemoglobin shows a paramagnetic property that disturbs the local magnetic field and decreases the MR signal (Thulborn et al. 1982). A higher MR signal reflects the effect of an increased proportion of oxygenated vs. deoxygenated haemoglobin, i.e. the BOLD effect, coupled with increased neural activity. In a task-based fMRI study, researchers can infer that a mental function is associated with a specific brain region by identifying changes in the BOLD signal in the brain region. Therefore, the discovery of the BOLD effect is essential for brain mapping, i.e. to map the location of brain activation associated with functions (Jenkinson and Chappell 2018).

1.2.5.2 Perfusion MRI – Arterial Spinning Labelling

A major limitation of the BOLD fMRI (also see Section 2.1) is that the BOLD signal should be interpreted in a relative sense, as the difference of brain signals between different conditions. The value from fMRI data per se cannot be directly referred to the actual neural activity. Some factors other than neural activity, e.g. CBF or vessel volume, may influence the BOLD signal. Perfusion MRI, in contrast, assesses the delivery of cerebral blood and provides a quantitative measure that can be linked to the actual state of blood perfusion by the unit ml/100 g/min for the volume of blood passing 100 g of tissue within one minute (Jenkinson and Chappell 2018). The basic concept of perfusion MRI is to label part of the blood flow and detect the labelled marker after a fixed time delay. Then, the change of the labelled content against time can be quantified. In arterial spinning labelling (ASL), water molecules are used as an intrinsic marker. In ASL-MRI, labelling is achieved by altering the magnetic properties of the hydrogen nuclei (i.e. their spinning behaviour) using different radiofrequency. Because changes in CBF can be a critical characteristic of neurological disorders, perfusion MRI has become an important tool for diagnosing neurodegenerative disorders, tumours and migraines (Telischak et al. 2015).

1.2.6 General Considerations of the Limitations of Neuroimaging Methods

Though most of the neuroimaging methods have been developed for decades, their application has some limitations. One of the most critical considerations for all imaging methods is the spatial and temporal resolution of imaging. For both structural and functional neuroimaging methods, a poor spatial resolution renders it hard to localize the precise position of a specific brain region. The problem of low spatial resolution is significant in PET, which investigates the brain by a voxel sized between 5 and 10 mm^3 (Gazzaniga et al. 2019). Therefore, it provides spatial information at the scale of gross anatomy. However, by using different radioactive neurochemical agents, PET can detect the part of the brain which specifically engages with the agents. The problem of lower spatial resolution is also significant in magnetic resonance spectroscopy (MRS).

Because MRS signals are relatively weak, to increase the signals obtained in a voxel, a larger voxel will be required for an MRS scan (Gazzaniga et al. 2019). Due to the limitation of spatial resolution, neuroimaging methods provide less information about brain features at the cellular level.

Temporal resolution is a critical factor for functional neuroimaging. For functional studies, the fundamental question would be 'do we have a fine resolution to capture the mental functions we desire to see?'. Some mental processes may last for minutes, such as the feeling of a bad mood. In contrast, some mental processes may arise transiently, such as shifting one's attention from one thing to another. Therefore, selecting a tool that is also fast enough to capture the different mental experiences is very crucial. MRI is limited at its temporal resolution due to the longer scanning interval (i.e. a lower sampling rate, such as two seconds for a scan) and the 'sluggish' hemodynamic response. In contrast to MRI, EEG and MEG are more sensitive to a quick mental process, with a temporal resolution in milliseconds (Gazzaniga et al. 2019). Further considerations of the pros and cons of MRI are outlined in Section 2.1.

1.2.7 Summary

- The brain and mental functions, sometimes metaphorized as a 'black box', can hardly be examined directly at the chairside. Therefore, a pivotal step to facilitate the investigation of the brain is to develop the technology for quantifying brain structure and functions.
- Neuroimaging is a non-invasive approach that visualizes the CNS, especially the brain.
- One of the major goals of using structural MRI is to investigate the morphology, including the size and shape, of the anatomical structure of the brain.
- The functional MRI methods investigate the brain signals associated with brain functions, including BOLD fMRI and perfusion MRI.
- The BOLD fMRI detects the changes in the proportion of deoxygenated and oxygenated haemoglobin in the brain. This metabolic event is indirectly associated with neural activity.

1.3 How Does Neuroimaging Contribute to Clinical Practice?

1.3.1 Introduction

How can neuroimaging contribute to dental practice? Intuitively, it is hard to imagine that the knowledge of 'brain activation' would contribute anything for dentists to complete a Class II cavity restoration. However, the functional perspective of the brain–stomatognathic connection (Figure 1.1) highlights the association between the brain, mental functions and oral functions. Therefore, understanding the brain is the key to understanding the individual variation in oral functions and feeding and oral healthcare behaviour. In the following sections, we elaborate this association by examples of dental neuroimaging studies. Firstly, we discuss the contribution of neuroimaging to oral neuroscience. Secondly, we discuss the contribution of neuroimaging to the clinical disciplines of dentistry.

1.3.2 Links Between Neuroimaging and Key Issues of Oral Neuroscience

As a new discipline of neuroscience, how does neuroimaging help investigate these key issues of oral neuroscience? Table 1.2 shows that neuroimaging research has been engaged with all the key issues in oral neuroscience (Iwata and Sessle 2019). For example, in terms of the pathway of pain processing, neuroimaging research extended our understanding of the circuitry from the spinal mechanism to brain mechanisms, showing cortical and subcortical activation associated with acute and chronic orofacial pain (Brügger et al. 2012; Gustin et al. 2011) and complicated mechanisms of pain modulation (Desouza et al. 2013; Gustin et al. 2012; Moayedi et al. 2012; Younger et al. 2010). Importantly, because neuroimaging research is conducted in human subjects, psychosocial factors, such as emotional and attentional factors related to pain, can be investigated (Weissman-Fogel et al. 2011; Abrahamsen et al. 2010; Youssef et al. 2014). Neuroimaging also helps to reveal the brain mechanism of swallowing and chewing (Lowell et al. 2012; Quintero et al. 2013). Notably, by directly assessing the dental patients who received treatment, translation between clinical practice (e.g. installation of denture prosthesis) and neuroscience can be achieved (Kimoto et al. 2011; Luraschi et al. 2013). Also, the perceptual processing of oral functions, which relies on self-reports from human subjects, including tactile and gustatory senses, can be studied using neuroimaging (Nakamura et al. 2011; Trulsson et al. 2010). As an *in vivo* imaging method, neuroimaging has become the crucial method for studying the perceptual and psychosocial aspects of oral functions, which are difficult to approach with animal models.

1.3.3 Links Between Neuroimaging and Clinical Disciplines of Dentistry

Clinically, neuroimaging research may help dental professions to understand the association between mental functions and dental treatment. For example, dentists may need to know the sensory processing of a patient who is chewing with an implant-supported denture. If a dental implant alters the sensory feedback from occlusion, one should expect to identify changes in cortical activation at the sensory area when subjects are chewing. Neuroimaging would be a suitable tool for the study related to the treatment outcomes of dental practice.

1.3.3.1 Prosthodontics

Restoration of both structural deficits and functional impairment is key to successful prosthodontic treatment. For patients with tooth loss, replacing the missing teeth with a dental prosthesis will restore structural deficits. Moreover, patients should adapt to the prosthesis and improve chewing function. Recent neuroimaging findings have shed light on the mechanisms of adaptation of dental prostheses (Table 1.3). For example, longitudinal research revealed that adaptation of a new denture was associated with not only the improvement of masticatory performance but also changes in brain activation in the somatosensory cortex (Luraschi et al. 2013). Consistently, tactile stimulation on dental implants was associated with brain activation of the somatosensory areas (Habre-Hallage et al. 2012). The findings suggest that changes in sensory feedback play a key role in improving oral functions by prostheses. Moreover, in partially edentulous patients, reduced occlusion was associated with reduced activation of the prefrontal cortex, and such reduced activation can be modulated by installing a denture (Kamiya et al. 2016). In patients with maxillary dental implants, tactile stimuli induced brain activation not only in the somatosensory cortex but also in the prefrontal cortex (Habre-Hallage et al. 2012). Changes in somatosensory and prefrontal activation were also identified in another longitudinal fMRI study that dentated patients were chewing a piece of gum when wearing a plate to cover their palate. The change in brain activation was associated with the recovery of masticatory performance, which was initially impaired (by the palatal plate) and later restored (Inamochi et al. 2017). These novel findings suggest that beyond sensory processing, the attentional and cognitive processing related to wearing a denture, as evidenced by the changes in the prefrontal cortex, may play a vital role in the adaptation of prosthodontic treatment. Thus, the neuroimaging findings provide new clues for prosthodontic treatment by highlighting the patient's adaptation to dental devices.

1.3.3.2 Periodontics

One of the primary roles of the periodontium is to support sensory feedback via the periodontal ligament. Neuroimaging would help clarify the neural pathway of sensory processing of periodontal stimuli (Kaneko et al. 2017; Kishimoto et al. 2019; Ono et al. 2015). Moreover, neuroimaging may contribute to elucidating the association between periodontal health and other systemic conditions (Table 1.3). A recently hotly debated issue is the association between dementia and neuroinflammation as well as neurotoxicity, which may relate to periodontal health (Tonsekar et al. 2017). To explore this brain–stomatognathic connection, researchers have directly assessed the association between periodontal health and the Aβ plaques of the brain, a critical feature of Alzheimer's dementia (Kamer et al. 2015). In this study, the pathological feature of Aβ plaque was assessed using PET, and the association between brain pathology and periodontal health (e.g. clinical attachment loss) can be quantified (Kamer et al. 2015). The association between oral health and other pathological brain features, such as lacunar infarction, can also be investigated using neuroimaging methods (Taguchi et al. 2013). Neuroimaging is a valuable tool for investigating the sensory pathway of periodontal inputs and the association between periodontal health and systemic conditions.

1.3.3.3 Orthodontics

Just like prosthodontic treatment, the success of orthodontic treatment is associated with patients' adaptation to the oral appliance. Again, the neuroimaging findings revealed that the use of the oral appliance is associated with an extended area of brain activation, not just confined to the somatosensory cortex (Horinuki et al. 2015; Ozdiler et al. 2019) (Table 1.3). In rats, experimental tooth movement was associated with changes in brain activity of the secondary somatosensory cortex and the insula (Horinuki et al. 2015). Critically, the animal model revealed that during tooth movement, brain activity change was also associated with inflammation, as identified by the expression of the inflammatory factors and macrophage infiltration in the periodontal tissue (Horinuki et al. 2015). The findings have demonstrated the strength of combined neuroimaging and histological approaches, which help elucidate changes in clinical symptoms and signs related to dental treatment.

1.3.4 Summary

- As an *in vivo* imaging method, neuroimaging has become the crucial method for studying the perceptual and psychosocial aspects of oral functions, which are difficult to approach with animal models.
- Recent neuroimaging findings suggest that beyond sensory processing, the attentional and cognitive processing related to wearing a denture may play a vital role in the adaptation of prosthodontic treatment. Neuroimaging research provides new clues for prosthodontic treatment by highlighting the patient's adaptation to dental devices.
- Neuroimaging is a valuable tool for investigating the sensory pathway of periodontal inputs and the association between periodontal health and systemic conditions.

1.4 The Brain–Stomatognathic Axis

1.4.1 Introduction

As addressed in Section 1.1, our understanding of oral functions will not be completed if we overlook brain functions. On the one hand, the CNS plays a crucial role in sensorimotor control of the oral apparatus. On the other hand, all the behaviours related to oral functions, including feeding and oral healthcare, are closely associated with general mental functions, including cognitive and affective processing. Therefore, from the functional perceptive, the brain and the stomatognathic system are both essential for maintaining oral health.

However, the brain–stomatognathic connection stated above is descriptive and does not fully explain the underlying mechanisms. The critical and yet unanswered question is 'how do the brain and the stomatognathic system work together to maintain our oral health?'. The question is difficult to answer because, before the advent of neuroimaging, researchers have had few tools to directly observe the brain mechanisms associated with oral functions in human subjects. In the following sections, we outline several theoretical frameworks for the brain–stomatognathic connection. The core concepts of the brain–stomatognathic connection are defined. Subsequently, three theoretical frameworks on the brain–stomatognathic connection are discussed. Finally, experimental design to test these theoretical frameworks are discussed.

1.4.2 Core Elements of the Brain–Stomatognathic Connection

Before discussing the brain–stomatognathic connection, we need to define the core elements of the connection. Particularly, we will clarify the functional element, i.e. the brain and the stomatognathic system, and human feeding behaviour.

1.4.2.1 Definition of the Functional Element

Based on the definition from Medical Subject Headings (MeSH) of the National Library of Medicine, USA, the stomatognathic system is defined as 'the mouth, teeth, jaws, pharynx and related structures as they relate to mastication, deglutition and speech' (MeSH 1986). By this definition, either intraoral structure (e.g. teeth and the tongue) or extraoral structure (e.g. the masseter) is part of the stomatognathic system since all the structure contributes to maintaining normal oral functions. Notably, from the functional perspective, our brain should also be considered as part of the functional element related to oral functions, even though the brain is not part of the stomatognathic system. Both cortical and subcortical regions are closely associated with oral functions (Figure 1.2).

1.4.2.2 Definition of the Behavioural Scope

Another core element to be defined is our behaviour that the brain–stomatognathic connection relates to. This book focuses on human eating and feeding behaviour, which is also the primary target for dental treatment. We define feeding behaviour as 'behavioral responses or sequences associated with eating including modes of feeding, rhythmic patterns of eating and time intervals' (MeSH 1969). However, we will need to revisit the definitions for several considerations. Firstly, our primary concern is the feeding behaviour of healthy adults. Eating disorders, such as anorexia and bulimia, are beyond the scope of our discussion. Secondly, the stomatognathic system is critical to speech (including the production of phonemes). The issues related to speech science and language production are not discussed in this book.

1.4.3 Theoretical Frameworks of the Brain–Stomatognathic Connection

There has been literature reporting the brain–stomatognathic connection for more than 100 years. However, most studies focused on the pathological mechanisms underlying diseases, such as the infectious routes between the brain and the head-and-neck regions. At present, very few frameworks have been proposed for the functional perspective of the brain–stomatognathic connection. By synthesizing recent clinical and experimental findings, in this section, we try to provide a 'big picture' regarding the brain–stomatognathic connection (Figure 1.3).

1.4.3.1 The Oral-to-Behaviour Framework

The most intuitive framework consists of the stomatognathic system as the only functional apparatus for feeding behaviour. According to

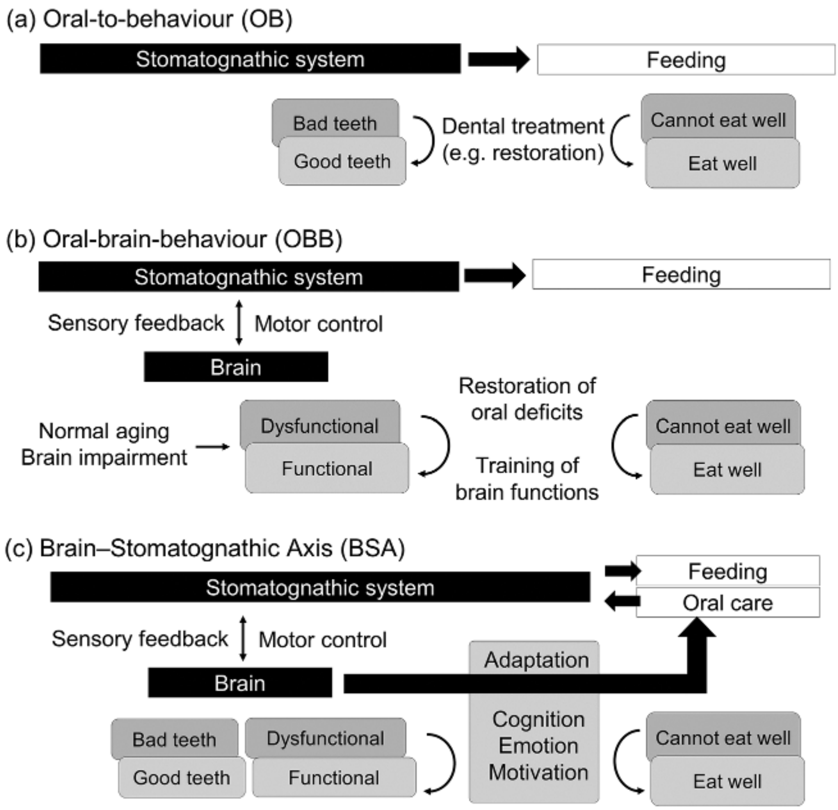

Figure 1.3 Theoretical frameworks of the association between the brain, oral functions and behaviour. (a) The oral-to-behaviour (OB) framework, (b) the oral-brain-behaviour (OBB) framework and (c) the brain–stomatognathic axis (BSA).

the oral-to-behaviour (OB) framework, a sound stomatognathic apparatus directly links to good eating and feeding behaviour (Figure 1.3a). Based on this framework, the structural and functional parameters of the stomatognathic system determine how well one can eat, such that the more teeth and the greater biting force one has, the better mastication and swallowing one will achieve. Notably, the OB framework consists of a bi-directional relationship: while improving the stomatognathic system will help better eating, a poor eating experience will motivate individuals to fix the deficits of the stomatognathic system. Empirically, the simple logic that ‘if you have got something wrong with eating, fix your teeth first’ goes well most of the time. It echoes the traditional view that dentists are trained as a surgeon who masters the surgical work in the oral cavity.

1.4.3.2 Challenges from the OB Framework

However, the OB framework may not always provide a good prediction of the outcome of dental treatment. For example, temporomandibular disorders (TMD) are associated with various deficits of teeth, the temporomandibular joint and muscles. According to the OB framework, a primary step of treating TMD would be to fix the structural deficits, such as adjusting patients’ occlusion by reshaping cusp morphology. However, cumulating evidence suggested that the relationship between occlusal adjustment and the improvement of patients’ symptoms is controversial (Xie et al. 2013). In contrast, more evidence from the sensorimotor control of limb movement has revealed that human action is maintained by the corresponding motor program, shaped by learning and adaptation via a complex mechanism of the brain (Wolpert and Flanagan 2016). Notably, the brain would also play a major role in the stomatognathic functions since most of these functions related to feeding – either mastication or swallowing or pain, are highly associated with the integration between sensory feedback and motor commands, both mandated by the brain. Therefore, to strengthen the original OB framework, the link between the stomatognathic system and behaviour needs to be revisited.

1.4.3.3 The Oral-Brain-Behaviour Framework

According to the oral-brain-behaviour (OBB) framework, to maintain good eating ability, one needs (i) to restore structural deficits of the oral cavity/teeth and (ii) to maintain the sensorimotor control of oral functions. Traditionally, point (ii) is relatively ignored in dental treatment because dentists assume that sensorimotor processing works well. However, as shown in Chapter 7, the sensorimotor processing of the brain may alter as age increases or in patients with brain impairment (e.g. neurodegeneration or stroke). Therefore, oral dysfunctions and difficulty in feeding may be associated with deficits in brain functions (Figure 1.3b). According to the OBB framework, for elderly or special needs patients, both fixing structural deficits and maintaining brain functions are critical to improving patients' oral health.

1.4.4 The Brain–Stomatognathic Axis

While the OBB model emphasizes that the brain is critical to the stomatognathic functions, it does not directly account for the individual differences in feeding behaviour. The OBB framework suggests that a good stomatognathic condition (e.g. fully dentated) and the integrity of sensorimotor control of oral functions both contribute to good eating ability. However, the framework simplifies the association between the brain and oral health. In addition to sensorimotor control (which has been widely investigated via animal research), mastication and swallowing are also associated with cognitive, affective and motivational processing of the brain (Figure 1.3c). For example, as shown in Chapter 5, the tactile (e.g. 'chewy') and gustatory (e.g. 'yummy') experience from chewing is associated with an increased hedonic value and reward processing of food. Therefore, the brain–stomatognathic axis (BSA) framework highlights multiple associations between brain functions and feeding behaviour. Most importantly, the BSA framework highlights that all the functions participate in the adaptation of oral conditions. When dysfunction occurs (either due to structural deficits, aging or brain impairment), individuals also learn how to adapt to this new condition. For example, when having a meal, the patients with a new denture may keep on detecting if the denture is well fitted and judging if the food bolus is good to swallow. All the cases suggest that feeding behaviour is not a simple translation of oral sensory and motor functions. It is crucially associated with the attentional, cognitive, motivational and emotional processing related to eating.

In the BSA framework, the term 'axis' emphasizes a bi-directional and dynamic relationship between the brain and the stomatognathic system (Lin 2018). In gastroenterology, the concept of 'gut-brain axis' (GBA) has been proposed and widely distributed for many years. The GBA consists of 'bidirectional communication between the central and the enteric nervous system, linking emotional and cognitive centres of the brain with peripheral intestinal functions' (Carabotti et al. 2015). In parallel, the BSA emphasizes that the brain plays a more comprehensive role in sensorimotor and affective–cognitive processing on the stomatognathic functions and feeding behaviour.

1.4.5 How Can Neuroimaging Research Help Studying the Brain–Stomatognathic Connection?

One of the greatest advantages of neuroimaging is to explore the brain mechanisms associated with feeding behaviour directly on human subjects. For example, researchers can measure the signals related to brain activities associated with chewing and swallowing with different imaging approaches. The following sections focus on research design for investigating the brain–stomatognathic connection.

1.4.5.1 Investigation of the OBB Framework

The OBB framework highlights sensorimotor control of oral functions. The brain mechanisms associated with oral functions can be investigated using a task-based study, in which brain activities are recorded concurrently when an individual is performing an oral function. The association between sensory or motor processing and oral functions can be modulated by different experimental conditions. For example, when chewing harder food, one should expect stronger sensory feedback from the periodontal tissue than soft food. In this case, changes in brain activation, as shown by functional MRI, would be identified at the somatosensory cortex, and this activity is known to reflect the intensity of sensory inputs (Onozuka et al. 2002; Takahashi et al. 2007). It is noteworthy that the interpretation of an association between task parameters (e.g. the hardness of food) and brain features (e.g. activation of the motor cortex) may be complicated. For example, when chewing a harder piece of food, one may pay more attention to the texture of the food. Therefore, the brain regions with activation may be associated with attention and cognitive control as well as sensory processing (Onozuka et al. 2002, Takahashi et al. 2007).

1.4.5.2 Investigation of the BSA Framework

In contrast to the OBB framework, the BSA framework additionally highlights the importance that the brain will actively adapt to the environment so that even though the functional apparatus is impaired (e.g. losing teeth), individuals can maintain feeding behaviour. A critical step to test this general hypothesis is to focus on the individuals who show structural deficits (e.g. with a higher number of missing teeth) but maintain a good oral function. In this group, the degree of sensorimotor adaptation and learning is assessed using specific tasks (see Chapter 8). The association between task performance and brain activation, particularly in the regions associated with cognitive, affective and motivational processing, is assessed using neuroimaging. Notably, the superiority of neuroimaging is that it can assess brain activation associated with complicated processing of learning and adaptation in human subjects – which may be challenging to perform on animal subjects.

1.4.6 Summary

- The OB framework consists of the stomatognathic system as the only functional apparatus for eating and feeding behaviour. According to the OB framework, a sound stomatognathic apparatus means good feeding behaviour.
- The OBB framework highlights the role of the exchange of sensorimotor information between the brain and the stomatognathic system in oral functions.
- In the BSA framework, the brain is not just a passive translator for the sensorimotor information but also a 'moderator' that actively engaged with one's feeding behaviour.
- Neuroimaging research on the BSA framework focuses on identifying individual differences in oral functions. The BSA emphasizes that the brain plays a more comprehensive role in sensorimotor and affective–cognitive processing on the stomatognathic functions and feeding behaviour.

Further Readings

Please see the Companion Website for Suggested Readings.

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