

# **Dietary Monitoring for Diabetes & Obesity: Detection and Quantification of Chewing Behavior - Background and Phenomenology\***

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## **Abstract**

An important component of maintaining a healthy lifestyle is a healthy diet. Dietary monitoring can be effected using wearable sensors or computers, networked to achieve dense communication with one or more monitoring and analysis nodes. Dietary monitoring sensor modalities include motion, acoustic signals, electrical signals from muscles, and analysis of facial imagery from video sequences.

In this technical summary, we overview the role of video-based detection and quantification of chewing behaviors for dietary monitoring. Section 1 overviews the context of mastication in health diet, and details techniques by which chewing has been detected in previous work. Section 2 discusses the neurophysiological basis for chewing, and overview the work of Cutler et al. in the detection and quantification of periodic motion. Original papers are abstracted, and bibliographies are reproduced at the end of this summary. Section 3 overviews the application of Cutler's work to the analysis of video imagery containing facial regions in which chewing behavior is manifest. Preliminary conclusions are presented in Section 4.

## **1. Introduction**

As noted by Amft et al.(2005), given current trends of supralinearly increasing health care costs, and rapid growth in the aging population, health care and maintenance of a healthy lifestyle are important socio-economic issues. As a result, individuals, health insurance companies, and government agencies are investing considerable resources to develop tools that help people maintain healthy living habits. Amft et al. provide in-depth discussion of this trend, which publication contributes strongly to the remainder of this section.

Technical support for healthy living includes wearable health monitoring devices, based on ubiquitous computing technology. These devices help combine long term physiological monitoring and behavioral analysis with personalized direct or feedback, to assist users in reducing their risk of obesity, diabetes, and cardiovascular disease. In this study, we concentrate upon exercise and diet. In this technical summary, we focus on the monitoring of chewing behavior, which is a constituent of dietary monitoring.

In general, dietary monitoring includes a variety of emphases and approaches, starting from nutritional composition of one's diet to frequency, duration and speed of eating, all of which are relevant to health issues. Today, monitoring of these behaviors is done almost entirely by user questionnaires. Electronic devices are used as intelligent log books that can derive long term trends, calculate calories from entered data, and give simple user recommendations. Data collection and entry is performed by the user, which involves considerable effort, and significant error through non-compliance.

Since disease prevention involves the adaptation of a healthier lifestyle, long term, quasi-permanent monitoring over time scales of months or years is needed to reduce the incidence of obesity, diabetes, and the risk of cardiovascular disease. As such, our goal is to accurately monitor caloric intake, with a specific degree of precision. We believe that via a combination of wearable sensors and some environmental augmentation, useful assistive dietary systems are feasible. Such systems could provide an estimate of food consumption, as well as caloric expenditure, similar to modern physical activity monitoring devices. Additionally, such devices could be used as data entry assistants that would (1) monitor food intake, (2) present the user

with a best estimate of when, how much, and what he has eaten, then (3) ask the user to correct food intake errors and substitute more nutritious items in future dietary activities.

In practice, it is possible to implement a multi-sensor approach to non-invasive food intake monitoring support using the following four components:

- (a) detecting and analyzing chewing behavior from video imagery;
- (b) detecting and analyzing chewing sounds (Amft et al., 2005);
- (c) using electrodes mounted on the base of the neck (e.g. in a collar) to detect and analyze bolus swallowing; and
- (d) using motion sensors on hands to detect food intake related motions, such as moving a utensil toward one's mouth, or taking food from a serving bowl.

Alternatives c) and d) (electromyography and motion sensors), while interesting and of future utility, are not the focus of this technical summary, which emphasizes the computer analysis of video imagery to obtain information about chewing behaviors and their duration.

Along similar lines and relevant to b), above, Amft et al. have shown that good-quality chewing sound signals can be obtained from a microphone placed in the ear canal. Since much of the acoustic signal generated by the mechanical interaction of teeth and food during mastication is transmitted by bone conduction, these sounds are significantly more intense in the ear canal than most speech signals. Also, the ear canal is an unobtrusive location for an acoustic sensor, and has been proven acceptable in applications such as hearing aids or mobile phone headsets.

Amft et al. also show that sounds from chewing can be discriminated from a signal containing a mixture of speech, silence, and chewing sounds. The authors present a method that detects the beginning of single chews in a sequence of chewing activity, and show that acoustically-based discrimination between different kinds of food is possible with high accuracy.

In this study, pursuant to item a), above, we propose to perform a similar task with computer-based analysis of video sequences that contain images of persons chewing. We propose to first segment and co-register sub-images that contain chewing images, to provide a systematic basis for consistent comparison between images. Secondly, we propose to compute the similarity matrix of an  $N$ -image sequence, then compute the autocorrelation of the similarity matrix, after Cutler and Davis (1999). Thirdly, the power spectrum of the autocorrelation matrix will be computed, and the resulting spectrum will be compared to the spectral analysis results of known chewing, talking, and yawning behaviors. Fourthly, the resultant hypothesis will be further analyzed using a model-based approach, to determine the type and duration of the chewing behavior.

## **2. Related Work**

### **2.1. Physiological Basis for Chewing** (from Nakamura et al. (1995))

Mastication is a typical rhythmic behavior in mammals. Like respiration, it is generally accepted that the motor command for the basic pattern of rhythmic oral-facial movements is generated by a neuronal population in the brainstem (central pattern generator, CPG). The central pattern generation of rhythmical masticatory movements can be divided into three processes:

- (1) generation of the masticatory rhythm;
- (2) generation of a pattern of activities of the jaw, tongue and facial muscles; and
- (3) coordination of the activities of these muscles.

There are several lines of evidence that the masticatory CPG is functionally subdivided into two neuronal groups: one for generation of the masticatory rhythm, giving the timing signal for rhythmical alternation of jaw closing and jaw opening (central rhythm generator, CRG), and the other for generation of the spatiotemporal pattern of activities of the jaw, tongue and facial muscles. This review, abstracted from Nakamura et al. (1995) will examine the localization of the CRG for rhythmical masticatory jaw movements, sources for its activation, and the premotor neurons mediating its output to the trigeminal motoneurons. Next, we will discuss the neurochemical basis for rhythmical trigeminal motoneuron activity as well as central masticatory rhythm generation.

Mastication is one of the most common rhythmic behaviors in mammals along with respiration and locomotion. Though actual jaw movements during mastication show various patterns among animal species depending on the food ingested (carnivore, herbivore or omnivore) (Hiemae, 1978; Lund, 1991), there are two common features in the masticatory jaw movements: (1) rhythmical alternation of jaw-closing and jaw-opening movements, and (2) changes in the pattern of movement during a masticatory sequence from ingestion of food into the mouth to its deglutition, so as to fit the pattern of jaw movement as well as the bite force to the properties of food in the mouth (Lund and Olsson, 1983).

Accordingly, the neural mechanisms responsible for generation of rhythmical movements and those for modulation of motor command by sensory feedback from the oral-facial area have been the two major issues in the studies of the neural mechanisms controlling masticatory movements. It is now generally accepted that (1) the basic motor command for the rhythmical movement is generated by a certain central neuronal population, and (2) the central motor command is modulated by sensory information of the properties of food in the mouth as well as kinesthesia of the jaw, tongue and face. In a recent review, Rossignol and Dubuc (1994) have concisely defined the current concept of 'central pattern generator' as "an operational expression to designate an ensemble of neural elements whose properties and connectivity can give rise to characteristic patterns of rhythmic activity in the absence of external feedback."

The basic components of masticatory movements are (1) the rhythm or cycle length of the movement, (2) the pattern of activity of the jaw, tongue and facial muscles (duration and amplitude of EMG burst activity during a cycle) and (3) the coordination of the activities of these muscle groups. The central pattern generation of mastication involves the central processes for production and regulation of the neuronal activities underlying these three components.

It was reported that the rhythm and the activity of jaw muscles in rhythmical jaw movements (RJMs) could be varied independently from each other. Lund et al. (1984) studied the patterns of EMG of jaw muscles and the jaw movement induced by repetitive stimulation of the cerebral cortex of anesthetized rabbits, the head of which was fixed to a stereotaxic apparatus. The jaw movements were monitored three-dimensionally by movements of a small lightbulb attached to the mandibular symphysis. They found that an increase in intensity of repetitive stimulation of one point in the cerebral cortex in the rabbit caused an increase in the frequency of the rhythm with no changes in the spatial pattern of jaw movement, while that of another point increased the amplitude of jaw movement and jaw muscle EMG activity but exerted no influence on the frequency of the rhythm. Chandler and Tal (1986) found that transection of the brainstem at a certain level reduced the amplitude of the digastric (jaw-opening) muscle EMG without exerting significant effects on either the cycle duration or the burst duration of the digastric EMG of RJMs induced by stimulation of the cerebral cortex in the guinea pig.

Likewise, Chandler et al. (1985c) reported that after systemic strychnine administration, the frequency of cortically induced RJMs showed virtually no changes, while the burst duration of the digastric EMG was markedly increased in the guinea pig. Furthermore, it was reported that tonic application of load to the mandible increased only the amplitude and duration of the masseter (jaw-closing) EMG burst, and exerted no effects on the frequency of RJMs induced by systemic application of apomorphine (a dopamine agonist) in the guinea pig (Chandler et al., 1985b). Thus it can be assumed that the central pattern generator for mastication is functionally subdivided into two neuronal groups: one for generation of the masticatory rhythm, giving the timing signal for rhythmical alternation of jaw-opening and jaw-closing, and the other for generation of the spatiotemporal pattern of activities of the jaw, tongue and facial muscles, in the same manner as proposed by Feldman et al. (1988) for the central pattern generation of rhythmical respiratory movements.

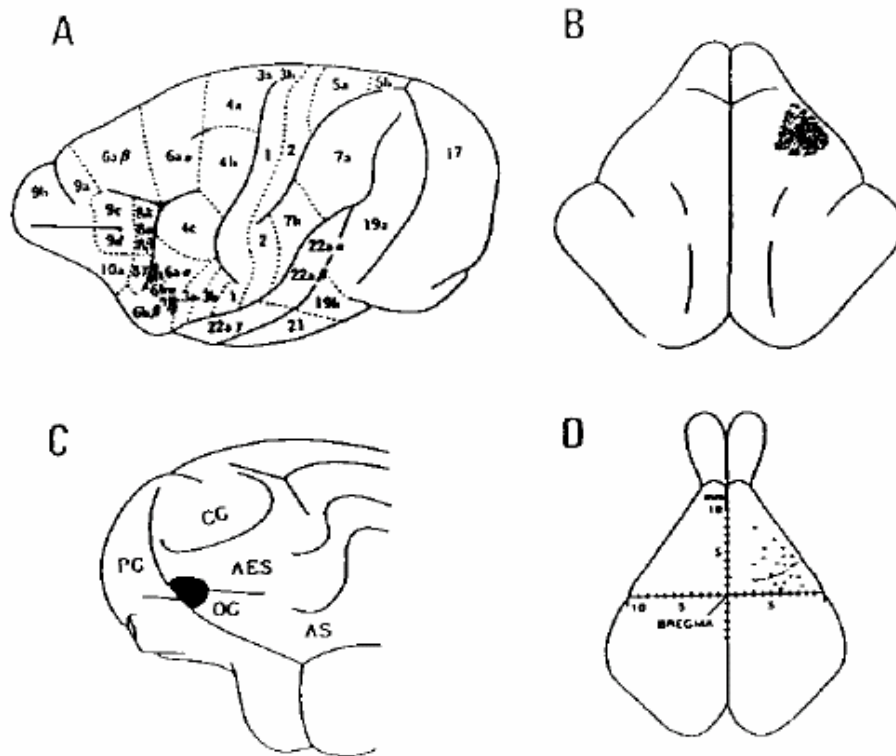
This technical summary designates the central neuronal population for the rhythm generation as the 'central rhythm generator' (CRG). The central motor command for the actual pattern of the masticatory movement is assumed to be generated by a certain neuronal population, which receives rhythmical input from the CRG, integrates the input with other central and peripheral inputs and sends the command to cranial motoneurons innervating the jaw, tongue and facial muscles.

## **2.2. Central Generation of Masticatory Rhythm**

Repetitive electrical stimulation of a certain area of the cerebral cortex induces RJMs in many species, including monkey (Vogt and Vogt, 1926), rabbit (Bremer, 1923; Kawamura and Tsukamoto, 1960; Sumi, 1969; Dellow and Lund, 1971), cat (Magoun et al., 1933; Morimoto and Kawamura, 1973; Nakamura et al. 1976; Nakamura and Kubo, 1978), guinea pig (Goldberg and Tal, 1978; Nozaki et al., 1986a) and rat (Sasamoto et al., 1990; Zhang and Sasamoto, 1990). The RJM is accompanied by a coordinated rhythmical tongue movement as well as secretion of saliva. Thus, the cortically induced oral-facial behavior as a whole strongly resembles natural mastication. Accordingly this area has been called the cortical masticatory area (CMA), as shown in Figure 1.

Natural masticatory movements change the pattern of jaw movements during a masticatory sequence from ingestion of food into the mouth to its deglutition. Schwartz et al. (1989) divided the masticatory sequence in the awake rabbit into three consecutive series on the basis of the trajectory of the jaw movement and the pattern of jaw muscle EMG (Fig. 2). The food ingested into the anterior part of the oral cavity is transported posteriorly between the upper and lower molar teeth (preparatory series). Then the food is torn or crushed between the upper and lower teeth (reduction series), which is followed by another process preceding swallowing (preswallowing series).

Bremer (1923) induced three types of RJMs by repetitive electrical stimulation of the cerebral cortex in awake rabbits. The first was incisal gnawing elicited from the most anterior part of the CMA, consisting of a very rapid, small-amplitude movement predominantly in the anteroposterior direction. Stimulation of the middle part of the CMA induced vertical jaw movements of larger amplitude. Stimulation of the posterior part of the CMA induced jaw movements in the lateral directions reminiscent of the ruminatory or milling-type mastication. Lurid et al. (1984) induced the latter two types of RJMs by stimulation of the CMA in the anesthetized rabbit: the vertical jaw movement was induced from the rostromedial part and the milling-type movement from the caudolateral part of the CMA.

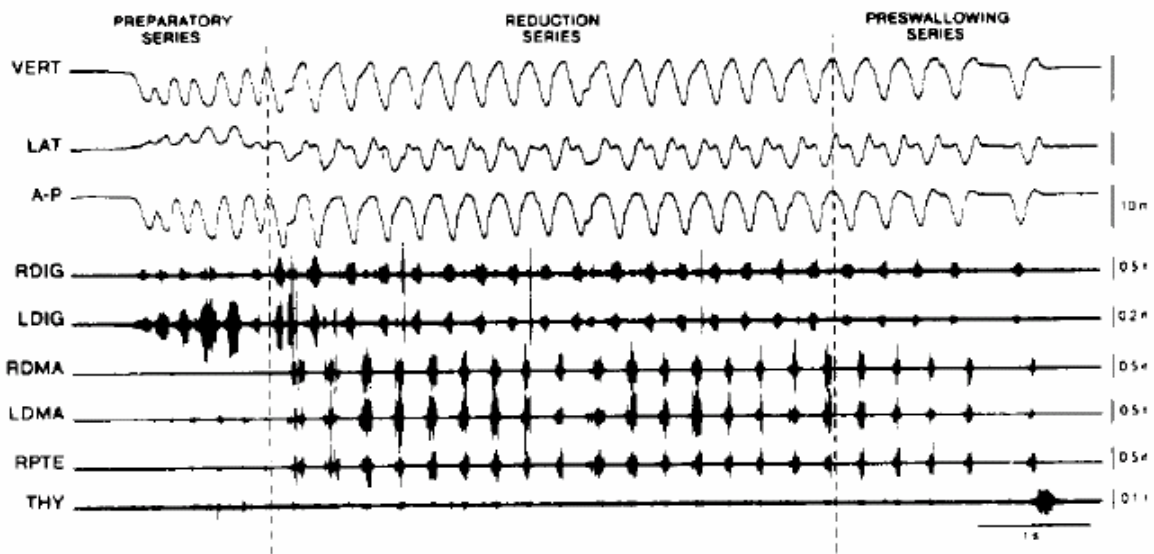


**Figure. 1.** Cortical areas inducing masticatory-like movements (cortical masticatory area). A, long-tailed monkey (area 6ba) (from Vogt and Vogt, 1926). B, guinea pig (shown as black area) (from Goldberg et al., 1982; with permission). C, cat (shown as black area) (from Morimoto and Kawamura, 1973; with permission). D, rabbit (shown with dots) (from Lurid et al., 1984; with permission). Abbreviations: AES, anterior ectosylvian gyrus; AS, anterior sylvian gyrus; CG, coronal gyrus; 0(3, orbital gyms; PG, proreate gyrus.

Liu et al. (1993) classified the cortically induced RJMs in anesthetized rabbits into four types on the basis of the different features of trajectories of the jaw movement:

- small circular (type A),
- large circular (type B),
- large vertical (type C) and
- crescent-shaped (type D)

Types B and D resembled the patterns of jaw movements during the food transport cycle and the chewing cycle in a natural masticatory sequence in the awake rabbit, respectively. Each characteristic pattern was induced from stimulation of separate points in the CMA.



**Figure 2.** Patterns of jaw movements and EMG of jaw muscles during a masticatory sequence of a pellet in a rabbit. A pellet was inserted into the mouth. It was transported posteriorly to the molar region (preparatory series), chewed (reduction series) and prepared for swallowing (preswallowing series). Upper 3 traces illustrate the jaw movements in the vertical, lateral and antero-posterior directions; jaw closure, movement to the left side, and protrusion are shown as upward deflections. Lower 6 traces show EMGs of jaw muscles and the thyrohyoid muscle (THY, bottom trace). Abbreviations: DIG, digastric muscle; DMA, deep masseter muscle; PTE, medial pterygoid muscle; R, right; L, left. THY EMG shows time of occurrence of swallowing (from Schwartz et al., 1989; with permission).

Likewise, two distinct types of RJMs, corresponding to the transport and chewing cycles, were induced by stimulation of separate points of the rat CMA (Sasamoto et al., 1990; Zhang and Sasamoto, 1990). Thus, repetitive stimulation of the CMA can induce RJMs which show a feature of only one type of jaw movement pattern during a natural masticatory sequence in awake animals. With this reservation, however, the RJMs induced by stimulation of the CMA in anesthetized animals cannot be differentiated from those during the natural masticatory sequence in awake animals. In addition, there are strong similarities in the pattern of EMG activities of jaw muscles between cortically induced and natural mastication: Hence, it is strongly suggested that the neuronal elements involved in the cortically induced RJMs also take part in the central pattern generation of natural mastication. Thus, the CMA-induced RJM has been used as a model of the natural masticatory jaw movement.

The rhythmical activity representing the cortically induced RJMs can be recorded from the branches of the trigeminal nerve innervating the jaw-closing and jaw-opening muscles. The rhythmical nerve activity can still be induced by repetitive CMA stimulation after the animal is paralyzed (fictive mastication) (rabbit: Dellow and Lund, 1971; cat: Nakamura et al., 1976; Nakamura and Kubo, 1978), by application of muscle relaxants with a dose large enough to block neuromuscular junctions of the intrafusal as well as extrafusal muscle fibers (Carli et al., 1967). In addition, Dellow and Lund (1971) showed that fictive mastication was not due to afferent signals from the vascular or respiratory systems in the paralyzed isolated brainstem of rabbits, in which the branchial and cervical nerves had been sectioned. Thus, the cortically

induced rhythmical masticatory activity can be induced with no intervention of rhythmical afferent impulses from the periphery, indicating that the timing signal for the masticatory rhythm is generated by a certain neuronal population in the brainstem (central rhythm generator, CRG).

The rhythm of cortically induced RJMs is virtually constant, irrespective of the frequency of cortical stimulation within a certain range (e.g., 20-200 Hz) or when they are induced by application of cortical stimulation at a random frequency (Dellow and Lund, 1971). Consequently the CRG does not simply reduce the frequency of output from that of the input at a fixed ratio, but actually generates the rhythmical output from nonrhythmical inputs.

Fictive as well as real mastication was reported to be induced also by stimulation of a variety of subcortical structures, including the amygdala (rabbit: Kawamura and Tsukamoto, 1960; Lund and Dellow, 1971; cat: Nakamura and Kubo, 1978), the internal capsule, putamen, globus pallidus, substantia nigra, lateral hypothalamus, thalamic reticular nucleus, mesencephalic reticular formation and pyramidal tract at the pons (rabbit: Lund and Dellow, 1971). After decerebration, repetitive stimulation of the mesencephalic reticular formation and the pontine pyramidal tract still induced rhythmical jaw movements, indicating that the forebrain is not essential for induction of the rhythmical masticatory movements (rabbit: Lund and Dellow, 1971). In the ketamine-anesthetized guinea pig, Hashimoto et al. (1989) showed that repetitive electrical stimulation of the mesencephalic reticular formation at the level of the red nucleus induced RJMs, which were retained after decerebration and cerebellectomy but were abolished after a midline section of the midbrain. The rhythmical burst activity was still induced in the digastric motoneurons after the animal was paralyzed. The section of the pontine pyramidal tract abolished the rhythmical activity induced by the ipsilateral CMA stimulation, but not that induced by stimulation of the contralateral mesencephalic reticular formation. A unilateral lesion in the oral portion of the gigantocellular reticular nucleus, where the CRG for mastication is located (see below, Section 4), abolished the rhythmical activity induced by stimulation of not only the CMA but also the mesencephalic reticular formation on the contralateral side. Microinjection of L-glutamate into the dorsolateral mesencephalic reticular formation induced the rhythmical activities similar to those induced by repetitive electrical stimulation on the same site. Thus, activation of the neurons in the mesencephalic reticular formation can centrally induce rhythmical jaw movements via an extrapyramidal route, crossing to the contralateral side at the midbrain level and descending to the bulbar reticular formation.

In contrast, Chandler and Tal (1987) reported that repetitive electrical stimulation of widespread areas of the midbrain and pons suppressed ongoing cortically induced rhythmical digastric EMG activity. Upon comparison of the location of their stimulated sites inducing this suppression with the region inducing the rhythmical digastric activity found by Hashimoto et al. (1989), the latter is found to be located directly rostral and dorsal to the former at the level of the red nucleus, and exactly corresponds to the area from which Chandler and Tal (1987) did not obtain suppression of the cortically induced rhythmical digastric EMG activity. In addition, innocuous mechanical stimulation of the oral mucosa can also induce fictive as well as real masticatory movements in rabbit (Bremer, 1923; Lund and Dellow, 1971; Olsson et al., 1986), cat (Thexton, 1973), guinea pig (Goldberg and Tal, 1978) and rat (Van Willigen and Wejjs-Boot, 1984; Juch et al., 1985). It was also reported that RJMs can occur even spontaneously in the ketamine-anesthetized guinea pig (Goldberg and Tal, 1978).

### **2.3. Rhythmical Activities of Trigeminal Motoneurons in Association with Cortically Induced Fictive Mastication**

Intracellular recording from trigeminal motoneurons revealed that there was a striking difference in rhythmical inputs from the CRG between the jaw-closing and jaw-opening motoneurons during cortically induced fictive mastication. Intracellular potentials in jaw-closing motoneurons consisted of a rhythmical alternation of depolarizing and hyperpolarizing potentials, in coincidence with the jaw-closing and jaw-opening phases during fictive RJMs, respectively. The depolarizing and hyperpolarizing potentials consisted of excitatory and inhibitory postsynaptic potentials (EPSPs and IPSPs), respectively. In contrast, the jaw-opening motoneurons showed rhythmical depolarizing potentials (EPSPs) alone, superimposed by a burst of spikes, coincident with the jaw-opening phase, and no hyperpolarizing potentials between successive depolarizing potentials (cat: Nakamura and Kubo 1978, Kubo et al. 1981; guinea pig: Chandler and Goldberg 1982) (Fig. 4).

Chandler and Goldberg (1982) recorded intracellular potentials from jaw-closing motoneurons in the ketamine-anesthetized guinea pig during cortically induced and spontaneous RJMs. They found rhythmical hyperpolarizing potentials (IPSPs) coincident with the jaw-opening phase monitored by digastric EMG burst activity. The hyperpolarizing potentials persisted even after paralysis of the animal. It was suggested that the synaptic mechanisms for rhythmical intracellular potentials in trigeminal motoneurons during both spontaneous and cortically induced RJMs are similar to each other.

There is a marked difference in the distribution of muscle spindles between jaw-closing and jaw-opening muscles: there is a rich supply of muscle spindles in jaw-closing muscles, while virtually no spindles are found in jaw-opening muscles (Hosokawa, 1961). In natural mastication, jaw-closing muscles are stretched during the jaw-opening phase, which activates the muscle spindles in the jaw-closing muscles. The muscle spindle afferents potentially evoke the stretch reflex in the jaw-closing muscles (jaw jerk). If this stretch reflex is not inhibited during the jaw-opening phase, the jaw cannot open smoothly following the central motor command, because the jaw-closing muscles produce a much stronger force than the jaw-opening muscles. The inhibition of jaw-closing motoneurons during the jaw-opening phase can effectively suppress the jaw jerk during the jaw-opening phase, leading to a smooth jaw-opening according to the central command. On the other hand, even if the jaw-opening muscles are stretched during the jaw-closing phase in natural mastication, no stretch reflexes are evoked, and the jaw can close smoothly following the central motor command in spite of no inhibition of jaw-opening motoneurons (Kubo et al., 1981; Goldberg et al., 1982).

With respect to the central rhythm generation of RJMs, however, the rhythmical inhibition of jaw-closing motoneurons plays no essential role. After abolition of inhibitory synaptic transmission to the masseter (jaw-closing) motoneurons by injection of tetanus toxin into the masseter muscle in the non-paralyzed guinea pig, repetitive CMA stimulation induced rhythmical EMG bursts in the tetanus toxin-injected masseter muscle not only during the jaw-closing but also during the jaw-opening phase. After the animal was paralyzed, repetitive CMA stimulation induced rhythmical depolarizing potentials in trigeminal motoneurons innervating the tetanus toxin-injected masseter muscle coincident with the jaw-closing phase of fictive RJMs, but not hyperpolarizing potentials during the jaw-opening phase. The results indicate that the rhythmical inhibition of jaw-closing motoneurons is indispensable for smooth jaw-opening during natural mastication, but not essential for the central generation of the masticatory rhythm itself (Enomoto et al., 1985).

Chandler et al. (1985c) reported that the neural network for generation of the cortically induced masticatory rhythm in the guinea pig does not critically depend upon glycinergic inhibition, on the basis of the results that systemic application of strychnine (a glycine antagonist) minimally affected the rhythm. It is interesting that the rhythmical intracellular potential induced by repetitive CMA stimulation in cat hypoglossal motoneurons consists of only the rhythmical depolarizing potential (EPSP) superimposed by bursts of spikes (Sahara et al., 1988), if the fact is taken into consideration that there are virtually no muscle spindles in the tongue of the cat (Law, 1954; Blom, 1960) while there are many of them in the primate (Kubota et al., 1988).

Similar to suppression of the jaw-closing reflex during the jaw-opening phase of the rhythmical masticatory movement, the jaw-opening reflex evoked by innocuous stimulation of the oral mucosa is tonically inhibited throughout the masticatory sequence (Lund et al., 1981). This tonic inhibition is superimposed by a further phasic inhibition during the jaw-closing phase of real RJMs induced by repetitive CMA stimulation in the rabbit. This may contribute to the smooth jaw closing during mastication, since the innocuous mechanoreceptive afferents from intraoral mucosa elicited by the food ingested potentially evoke the jaw-opening reflex. During fictive mastication in the anesthetized, paralyzed rabbit, the jaw-opening reflex in the digastric nerve evoked by innocuous stimulation of the lip showed the same pattern of tonic and phasic suppression as in the non-paralyzed rabbit (Lund et al., 1983). Consequently, the suppression of the jaw-opening reflex during mastication is induced centrally.

During cortically induced fictive mastication, the digastric motoneurons are not inhibited either tonically throughout the masticatory sequence or phasically during the jawclosing phase, indicating that the central inhibitory influences are exerted not on the digastric motoneuron itself but on premotoneuronal sites in the jaw-opening reflex arc. In fact, it was reported that the excitability of a majority of neurons in the trigeminal sensory complex receiving low-threshold mechanoreceptive afferents in the rabbit was decreased during mastication (Olsson et al., 1986).

In addition, the excitability of central presynaptic terminals of AB fibers in the inferior alveolar nerve in the guinea pig was found to be rhythmically modulated in a phase-linked manner during the cortically induced fictive masticatory cycle: it was decreased coincidentally with the digastric nerve burst activity (jaw-opening phase) and increased during the middle and late periods of the interburst phase (jaw-closing phase) (Kurasawa et al., 1988). Thus, presynaptic inhibition of peripheral inputs from primary afferents to interneurons in the jaw-opening reflex arc may contribute to the rhythmical modulation of the jaw-opening reflex evoked by innocuous stimulation of the intraoral structures during mastication.

Corresponding with the suppression of cortically induced RJMs evoked by repetitive stimulation of the midbrain and pons (Chandler and Tal, 1987), Gurahian et al. (1989) reported that repetitive electrical stimulation of the caudal pontine reticular nucleus and the gigantocellular reticular nucleus suppressed the cortically induced rhythmical EPSPs in jaw-opening motoneurons and rhythmical IPSPs in jaw-closing motoneurons in ketamine-anesthetized guinea pig, but that it exerted no effect on intracellular potential levels in either jawclosing or jaw-opening motoneurons. Thus, the suppression would be a result of inhibition of neurons involved in the central pattern generation of the masticatory RJMs.

## **2.4. Age-related Changes in Brain Regional Activity during Chewing** (Onozuka et al., 2003)

This section is abstracted from Onozuka et al. (2003), and provides an example of how the effects of chewing change with age. For instance, the force exerted by the jaws, as well as effects of chewing on brain activity, are found to be age-related.

Although age-related changes in mastication-induced brain neuronal activity have been suggested little is known in humans concerning the anatomical regions involved. Using functional magnetic resonance imaging (fMRI) during cycles of rhythmic gum-chewing and no chewing, Onozuka et al. (2003) examined the effect of aging on brain regional activity during chewing in young adult (19-26 yrs), middle-aged (42-55 yrs), and aged (65-73 yrs) healthy humans. In all subjects, chewing resulted in a bilateral increase in the blood oxygenation level dependent (BOLD) signals in the sensorimotor cortex, cerebellum, thalamus, supplementary motor area, and insula, and a unilateral increase in the right prefrontal area. In the first three regions, the signal increases were attenuated in an age-dependent manner, whereas, in the right prefrontal area, the converse was seen. The remaining two regions showed no significant differences with ages. These results indicate that chewing causes regional increases in neuronal activity in the brain, some of which are age-dependent.

**2.4.1. Previous Work.** In previous studies, chewing was shown to result in an increase in cerebral blood flow due to changes in internal carotid arterial blood flow (Suzuki *et al.*, 1994; Nakata, 1998). Using xenon-enhanced computed tomography to map the location of cerebral blood flow changes, investigators have found chewing induces widespread increases in blood flow in the fronto-temporal cortex, caudate nucleus, and thalamus (Sesay *et al.*, 2000). In addition, cerebral blood flow imaging, by positron emission tomography (PET), shows increased blood flow in the bilateral lower frontal and parietal lobes during gum-chewing (Momose *et al.*, 1997). Consistently in these studies, cerebral blood flow during chewing is reported to be higher in young adults than in the elderly, implying an age-related decline in the chewing-induced increase in cerebral blood flow.

However, because of the low spatial resolution of xenon-enhanced computed tomography and PET, it is difficult to identify the fine anatomical regions activated during chewing. Functional magnetic resonance imaging (fMRI) has provided a new tool for the testing of specific hypotheses about the anatomical regions involved in processing sensory and motor information in the human brain (Pulvermuller, 1999; Yancey and Phelps, 2001).

BOLD contrast fMRI not only detects small signal changes that are related to changes in the magnetization of protons within the blood (Ogawa *et al.*, 1992), but also provides enhanced spatial and temporal resolution (Meisenzahl and Schlosser, 2001). In this study, Onozuka et al. used fMRI to assess the effect of aging on brain regional activity associated with chewing in young adult, middle-aged, and aged intact humans.

**2.4.2. Materials and Methods.** Three groups of neurologically healthy subjects were included in this study: a young adult group (age 19-26 yrs; seven males and four females), a middle-aged group (age 42-55 yrs; five males and three females), and an aged group (age 65-73 yrs; eight males and five females). One subject in the young adult group and three in the aged group were excluded from the analysis due to a significant motion artifact. The number of remaining teeth in the young adult, middle-aged, and aged groups (mean + SE) was 28 + 0.2, 25 + 1.7, and 19 + 1.8, respectively.

In addition, the mean biting force (Kgf, mean ± SE), measured by means of an occlusal forcemeter GM10 (Nagano Keiki Seisakusyo, Ltd., Nagano, Japan), was 77.5 + 6.62 in the

young adults,  $53.4 \pm 7.41$  in the middle-aged, and  $26.7 \pm 4.07$  in the aged groups, respectively. In all subjects, mastication work was functionally normal. However, if there were chewing abnormalities, the experiments were carried out after dental treatment (*e.g.*, repair of artificial crowns or the wearing of partial dentures). Written informed consent was obtained from each subject after a full explanation of the experiment, and the protocol for the use of human subjects was approved by the Ethics Committees of the Yoro Central Hospital.

The task paradigm was periods of rhythmic chewing, at a rate of approximately 1 Hz, measured by means of a metronome (Kemsley *et al.*, 2003), of moderately hard gum ( $5.6 \times 10^4$  poise) separated by periods of no chewing (see Suzuki *et al.*, 1994; Onozuka *et al.*, 2002). This gum, without odor and taste components, was specially prepared in the General Laboratory of Lotte Co. Ltd. (Saitama, Japan). Each subject performed 8 cycles of 32 sec of rhythmic chewing and 32 sec without chewing.

For each subject, functional (T2 weighted) images, followed by an anatomical (T1 weighted) image, were acquired by means of a 1.5-T Horizon MRI scanner (General Electric, Fairfield, CT, USA). The functional images consisted of echo-planar image volumes which were sensitive to BOLD contrast in the axial orientation (TE = 44 ms, TR = 4000 ms). The volume covered the entire brain with a 64 x 64 matrix and 42 slices (voxel size = 3.75 mm x 3.75 mm x 4 mm, slice thickness = 3.8 mm, gap = 0.2 mm). Images with 64 volumes were acquired for this experiment.

**2.4.3. Data Analysis.** The first 8 volumes were discarded because of instability of magnetization. Head motion was monitored with the use of an analytical software package (MEDx, Sensor Systems, Inc., Sterling, VA, USA), and studies were rejected if a shift of greater than 0.75 mm (20% of voxel size) over the scanning time period was detected in any direction, since excess movement reduces both the spatial resolution and spatial fidelity. If head motion was < 0.75 mm, Onozuka *et al.* applied a motion correction program, AIR 3.0, to the obtained images (Mazziotta and Cherry, 1993). Independently, a correction for head motion was also applied with the use of SPM99 software (Wellcome Department of Cognitive Neurology, London, UK). Furthermore, motion artifacts, which may have been due to chewing, were removed by a low-pass filter of 1.5 sec, with MEDx software. Finally, Onozuka *et al.* confirmed that residual motion artifacts were less than 0.01 mm (0.267% of a voxel) in any direction.

The 128 successive functional images for each subject were normalized to the MNI template, provided by the Montreal Neurological Institute (Lutz *et al.*, 2000), and spatially smoothed with an 8-mm Gaussian kernel with the use of SPM99. Statistical analysis, based on the general linear model approach (Friston *et al.*, 1995), was used. Global changes in the BOLD signal were removed by proportional scaling. The resulting areas of activation were characterized in terms of peak height and spatial extent (> 20 voxels).

For quantitative evaluation of the increased fMRI signal seen during chewing, Onozuka *et al.* calculated the difference between the signals while chewing and not chewing and expressed it as a percent change in the signal in the absence of chewing. The resultant data were analyzed by ANOVA followed by Scheffé's *post hoc* test.

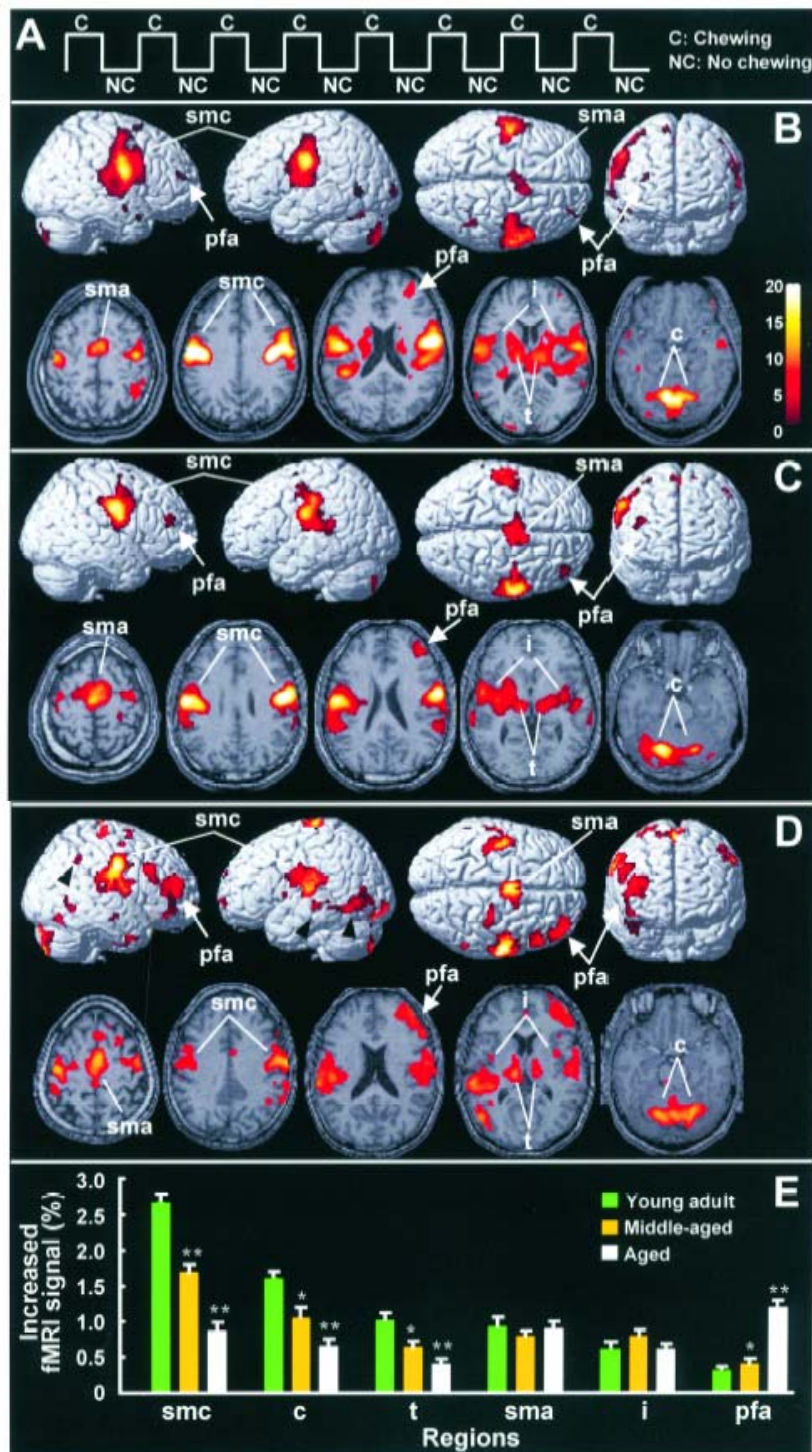
**2.4.4. Results.** In agreement with a previous finding (Onozuka *et al.*, 2002), in young adult subjects, gum-chewing was always associated with significant bilateral increases in the BOLD signal in the primary sensorimotor cortex, extending down into the upper bank of the operculum and insula (Fig. B). In addition, increases were seen in the supplementary motor area, thalamus, insula, cerebellum, and right prefrontal area. The locations of the most significant foci of activation for these regions are summarized in the Table, in which the anatomical regions with

maximal  $t$  values in clusters and the coordinates, as given in the Talairach and Tournoux (1988) atlas, are shown.

In contrast, in middle-aged subjects, the signal increase was lower in the primary sensorimotor cortex, thalamus, and cerebellum, and higher in the right prefrontal area, than in the young adults (Fig. C). In the aged subjects, these differences were even greater (Fig. D). Furthermore, in only the aged subjects, gum-chewing caused activation of the parietal, temporal, and occipital association cortices (Fig. D, arrowheads), the exact regions varying between subjects (data not shown).

Quantitative analysis revealed that the gum-chewing induced increase in the signal in the primary sensorimotor cortex of middle-aged and aged subjects was, respectively, 63.3% (group effect:  $F_{2, 25} = 59.41$ ,  $p < 0.0001$ ) and 32.7% (group effect:  $F_{2, 25} = 59.41$ ,  $p < 0.0001$ ) of that seen in young adults, while the corresponding values for the cerebellum were 65.9% (group effect:  $F_{2, 25} = 16.12$ ,  $p < 0.05$ ) and 40.5% (group effect:  $F_{2, 25} = 16.12$ ,  $p < 0.0001$ ), and those for the thalamus were 62.0% (group effect:  $F_{2, 25} = 12.34$ ,  $p < 0.05$ ) and 38.5% (group effect:  $F_{2, 25} = 12.34$ ,  $p < 0.001$ ) (Fig. E). In the prefrontal area, the signal increase in middle-aged and aged subjects was, respectively, 174.3% (group effect:  $F_{2, 25} = 27.58$ ,  $p < 0.05$ ) and 412.7% (group effect:  $F_{2, 25} = 27.58$ ,  $p < 0.0001$ ) of that seen in young adults. However, no significant difference was seen in the supplementary motor area (group effect:  $F_{2, 25} = 0.36$ ) or insula (group effect:  $F_{2, 25} = 1.01$ ).

**2.4.4. Discussion.** In this study, in agreement with previous PET (Momose *et al.*, 1997) and fMRI (Onozuka *et al.*, 2002) findings, gum-chewing significantly activated the oral region of the primary sensorimotor cortex, supplementary motor area, insula, thalamus, and cerebellum. These regions are believed to receive sensory information from the lips, tongue, oral mucosa, gingivae, teeth, mandibles, and temporomandibular joint and to control masticatory movement and the lingual and facial muscles (Nakamura and Katakura, 1995; Nakata, 1998), and therefore may be called the masticatory center (Nakamura and Katakura, 1995). The new finding of Onozuka *et al.* is that, in the primary sensorimotor cortex, cerebellum, and thalamus, the chewing-induced increase in the BOLD signal was attenuated in an age-dependent manner. Studies on aging and mastication have shown that the loss of teeth and the masticatory muscle power deficits seen with advancing age impair masticatory function, thereby causing a reduction in sensory input activity to the central nervous system (Okimoto *et al.*, 1991). In the present experiments, biting force was highest in the young adult group, followed by the middle-aged group, and lowest in the aged group. A similar age-dependent decline was seen in the number of remaining teeth. Taken together with the fact that age-related degeneration of various brain regions, including the somatosensory cortex, occurs in humans (Godde *et al.*, 2002), it may be suggested that the age-related attenuation of the signal seen in the above three regions results from an age-dependent decrease in both masticatory work and neuronal activity in the brain.



**Figure 3.** Effect of aging on brain regional activity during chewing. (A) The task paradigm used. (B,C,D) Significant signal increases associated with gum-chewing in a young adult subject (B), a middle-aged subject (C), and an aged subject (D). Upper section: Activated areas superimposed on a template ( $p < 0.05$ , corrected for multiple comparisons). Lower section: Activated regions superimposed on a T1 weighted MRI ( $p < 0.001$ , uncorrected for multiple comparisons).

*Abbreviations:* smc, primary sensorimotor cortex; sma, supplementary motor area; i, insula; t, thalamus; c, cerebellum; pfa, prefrontal area. Arrowheads: Activated regions in the parietal, temporal, or occipital association cortices. Color scale:  $t$  value (degrees of freedom = 87.12). (E) Percentage increase in the fMRI signal in the young adult (Y,  $n = 10$ ), middle-aged (M,  $n = 8$ ), and aged (A,  $n = 10$ ) groups. Each column represents the mean + SE. \* $p < 0.05$  compared with young adults. \*\* $p < 0.0001$  compared with young adults.

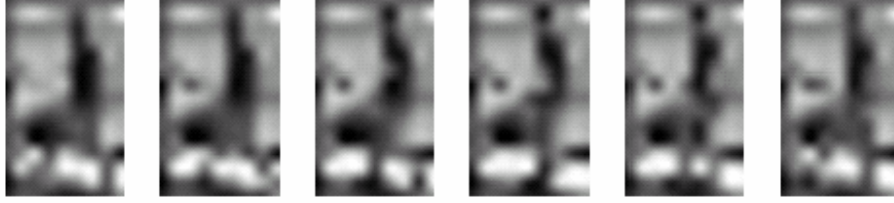
Surprisingly, the results of Onozuka et al. indicate that, in all groups, gum-chewing resulted in an increased BOLD signal in the right prefrontal area, and in aged subjects, this increase was 4 times higher than that seen in young subjects. A previous PET study found that patients with early Alzheimer's disease show increased activity in the prefrontal regions compared with healthy age-matched controls during cognitive tasks (Grady *et al.*, 2001a).

Furthermore, these authors also showed that increased right prefrontal cortex activity is associated with better memory performance in both groups (Grady *et al.*, 2001b); this has been interpreted as compensatory re-allocation of cognitive resources (Grady *et al.*, 2003). With respect to Alzheimer's disease and aging, the single most vulnerable circuit in the cerebral cortex is the projection referred to as the perforant path (Squire and Zola-Morgan, 1991), which originates in the entorhinal cortex and terminates in the dentate gyrus, thus providing the key interconnection between the neocortex and hippocampus (Amaral and Witter, 1989; Witter *et al.*, 1989). Thus, if the interpretation of Grady *et al.* is correct, it is possible that, in the elderly, chewing stimulates neuronal activity within a network between the right prefrontal cortex and the hippocampus, which might be useful in maintaining cognitive function. However, the exact link between gum-chewing and activation of the parietal, temporal, and occipital association cortices is unclear at the present time, and further research is required.

From Nakamura et al., we have seen that there is a known neurological basis for chewing behavior, including its regular rhythm and coordination of jaw, tongue, and facial muscles. The research of Onozuka et al. has further shown that chewing behaviors can be measured via analysis of functional MRI imagery, and that chewing can increase brain activity in elders. We next turn our attention to the measurement of manifestations of periodic behavior in video image sequences, in order to better understand the mechanism by which we propose to measure chewing behaviors from video imagery of patients undergoing dietary monitoring.

## **2.5. Real-Time Periodic Motion Detection and Analysis** (from Cutler and Davis, 1999)

Repetitive object motion is common in both nature and man-made environments. Perhaps the most prevalent periodic motions are the repetitive leg and arm movements that comprise human and animal locomotion. Examples include a person walking, a waving hand, a rotating wheel, ocean waves, and a flying bird flapping its wings. Other examples more pertinent to this study include facial distortions occasioned by chewing or talking. Since these motions are quasi-periodic, there is similarity between paired frames in a video sequence, such as that illustrated in Figure 4. Thus, image similarity is the key metric used by Cutler and Davis as a basis for quantifying periodic motion.



**Figure 4.** Low resolution image sequences of a periodic motion (a person walking on a treadmill). The effective resolution is 9x15 pixels.

In particular, the motion of a point  $\mathbf{x}(t)$ , at time  $t$ , is periodic if it repeats itself with a constant period  $p$ , expressed as

$$\mathbf{x}(t + p) = \mathbf{x}(t) + T(p),$$

where  $T$  denotes displacement. When  $p > 0$  is minimized to satisfy Equation (1), the associated *temporal frequency* is given by  $f = 1 / p$ . If  $p$  is not constant, then the motion can be cyclic in multiple spatial dimensions. Thus, in this study, we assume (after Cutler and Davis) that:

- (1) orientation and apparent size of the segmented objects do not change significantly during several periods (or do so periodically); and
- (2) video frame rate is sufficiently fast for capturing the periodic motion (i.e., the video rate is at least double the highest frequency in the periodic motion).

Following motion detection and object segmentation, one obtains a set of foreground objects  $O$ , each of which has a centroid and size. To detect periodicity for each object, Cutler and Davis first align the segmented object (for each frame) using the object's centroid, then resize the objects (using a Mitchell filter (Houtekamer et al., 2005)), so they all have the same dimensions. The scaling is required to account for apparent size change due to change in distance from the object to the camera. Because object segmentation can be noisy, the object dimensions are estimated using the median of  $M < N$  frames (where  $N$  is the number of frames in the video sequence to be analyzed). An object  $O_t$ 's self-similarity is then computed at times  $t_1$  and  $t_2$ . While many image similarity metrics can be defined (e.g., normalized cross-correlation, Hausdorff distance, etc.), perhaps the simplest is absolute correlation, which is given by

$$S_{t_1, t_2} = \sum_{(x, y) \in B_{t_1}} |O_{t_1}(x, y) - O_{t_2}(x, y)|,$$

where  $B_{t_i}$  is the bounding box of object  $O_{t_i}$ . In order to account for tracking errors, the minimal  $S$  is found by translating over a small search radius  $r$ , as follows:

$$S'_{t_1, t_2} = \min_{|dx, dy| < r} \sum_{(x, y) \in B_{t_1}} |O_{t_1}(x + dx, y + dy) - O_{t_2}(x, y)|.$$

For periodic motions,  $S'$  will also be periodic.

To determine if an object exhibits periodicity, we estimate the 1-D power spectrum of  $S'(t_1, t_2)$  for a fixed  $t_1$  and all values of  $t_2$  (i.e., the columns of  $S'$ ). In estimating spectral power, the columns of  $S'$  are linearly detrended and a Hanning filter is applied. A more accurate spectrum is estimated by averaging the spectra of multiple  $t_1$ 's to get a final power estimate  $P(f_i)$ , where  $f_i$  denotes the frequency of interest.

Periodic motion will manifest as peaks in the power spectrum  $P$ , which represent the fundamental frequencies associated with a given motion. A peak at frequency  $f_i$  is significant if

$$P(f_i) = \mu_P + k\sigma_P,$$

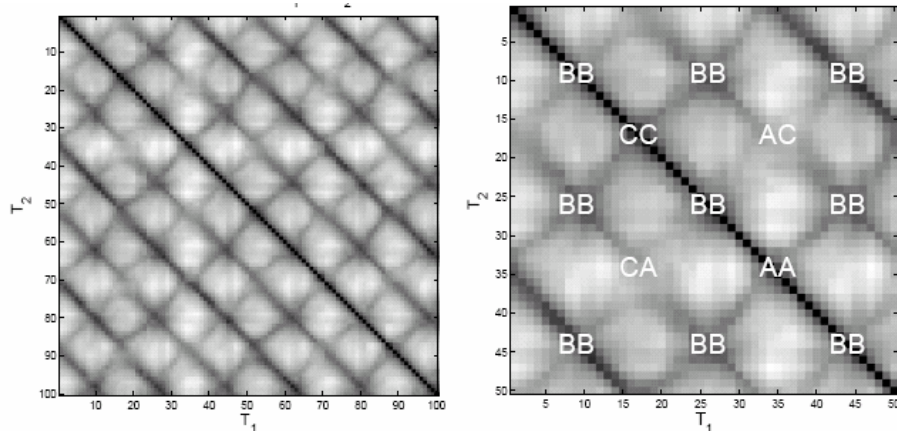
where  $k$  denotes a threshold value, with  $\mu_P$  and  $\sigma_P$  the mean and standard deviation of  $P$ . Note that multiple peaks can be present and are potentially significant to spectral classification (see Section 3 of this summary).

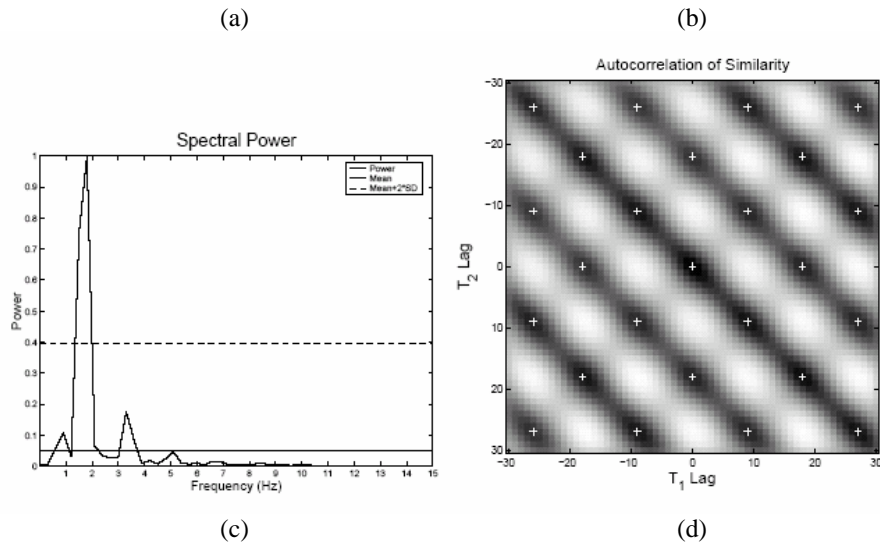
Cutler and Davis note that  $S'$  is a recurrence matrix, without the use of time-delayed embedded dimensions. Recurrence matrices are a qualitative tool used to perform time series analysis of nonlinear dynamical systems (both periodic and non-periodic). Recurrence matrices make no assumptions on the stationarity of the data, and do not require many data points to be used (a few cycles of periodic data is sufficient). The input for a recurrence matrix is a multi-dimensional temporally sampled signal. In our use, the input signal is the tracked object image sequence  $O_t$ , and the distance measure is image similarity. Given a recurrence matrix, the initial trajectory  $\mathbf{x}(t)$  of a point on an object can be recovered up to an isometry. Therefore, the recurrence plot encodes the spatiotemporal dynamics of the moving object. The similarity plot encodes a projection of the spatiotemporal dynamics of the moving object.

Given the similarity matrix  $S'$ , one can employ a short-time Fourier transform to analyze the temporal frequency characteristics of the encoded motion. Alternatively, it is possible to subject the autocorrelation of the similarity matrix to temporal frequency analysis to recover the characteristic frequencies  $\{f_i\}$ . The technique is well understood in signal processing, and is covered in detail in the excellent paper by Cutler and Davis (1999).

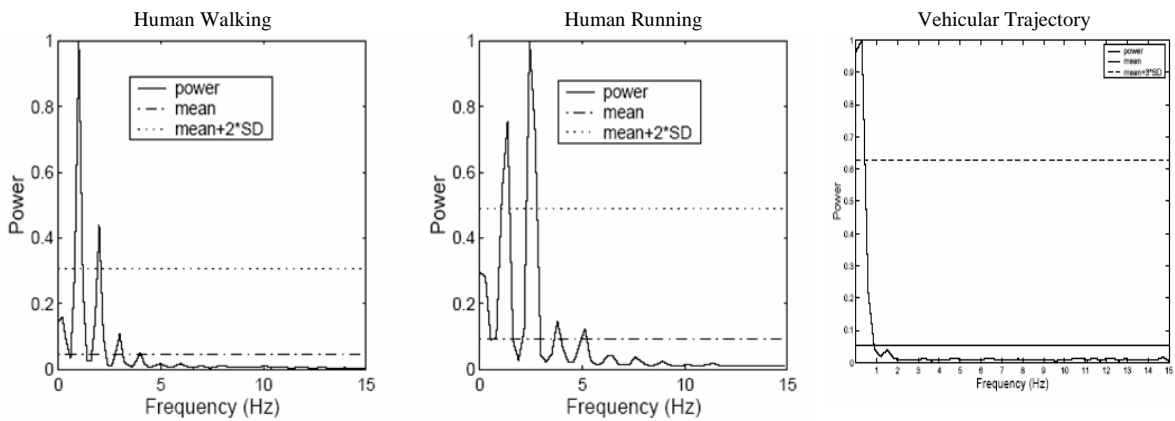
As an example of the use of a similarity matrix in quantifying dominant time frequencies in the image sequence of a man walking on a treadmill (Figure 4), consider Culter and Davis' results shown in Figure 5. Here, the similarity matrix (5a) is transformed into its autocorrelation (5d), and the temporal frequency plot is given in Figure 5c. Note the dominant frequency at approximately 1.8 Hz, which corresponds to the oscillatory behavior of the subject's legs.

The temporal frequency plot is also useful for classifying different types of motion, as shown in the results abstracted from Cutler and Davis (1999) that are included in Figure 6. Observe that the walking human has two dominant frequency peaks, as does the running human. However, the peaks specific to the running human are shifted toward higher frequencies, as expected, because the legs move faster when running. In contrast, the vehicle exhibits smooth, aperiodic motion, so there is an absence of dominant frequencies apart from the large DC peak.





**Figure 5.** Example results from Cutler and Davis (1999) for video sequence of man walking on a treadmill: (a) similarity matrix, (b) enlargement of similarity matrix, (c) temporal frequency spectrum, and (d) autocorrelation matrix.



**Figure 6.** Power spectral analysis of results (from Cutler and Davis (1999)) for (left to right) human walking, human running, and vehicle motion. Note the difference in the abscissal scale for the vehicle.

We next apply the findings of Cutler and Davis to the problem of detecting chewing motion from digital video sequences.

### 3. Image Analysis of Digital Video Sequences of Chewing Behavior

We begin our discussion of quantification of chewing behavior by noting that vertical movement of the lower jaw is common in humans during chewing, while lateral movement of the lower jaw is much less common, being more characteristic of ungulates. Additionally, in order to provide support for model-based refinement of chewing hypotheses, we propose to parameterize the visual manifestations of chewing, as follows:

- *Mouth* degree of openness (0 = closed, 1 = fully open)
- *Lips* degree of distortion (-1 = inverted, 0 = none, 1 = smile)
- *Jaw* speed of motion (expressed in Hz)

However, we also observe that model-based approaches can be inherently brittle, due to limited coverage. Therefore, our primary approach in the proposed study will be correlation-based, due to robustness in the presence of noise and unforeseen model configurations.

### 3.1. Initial Test Dataset

As the project progresses, we propose to gather four initial chewing sequences, to test our chewing quantification and classification algorithms:

- (1) Open mouth, slow mandible motion
- (2) Open mouth, fast mandible motion
- (3) Closed mouth, slow mandible motion
- (4) Closed mouth, fast mandible motion

These image sequences, together with several video sequences of the same subject talking and yawning, will comprise our initial dataset. Subsequent data gathering efforts will focus on a wider variety of mouth opening and jaw oscillation frequencies.

### 3.2. Proposed Prototype Algorithm

Given our preceding discussion of Cutler and Davis algorithm for estimating the periodicity of human or animal motion, we propose to develop the following prototype algorithm for video image analysis:

- Step 1.** Segment mouth and jaw as objects  $O_t$ , then co-register uniformly-sized frames
- Step 2.** *Auto-correlate* similarity matrix of mouth and jaw objects  $O_t$ , to produce autocorrelation matrix  $A$
- Step 3.** Average Fourier spectra of rows of  $A$  to produce a *motion spectrum*  $P$
- Step 4.** Classify motion spectrum from Step 3, to produce *motion hypothesis*  $H$ . For example,  $H$  could be *chewing, talking, yawning*, etc.

It is then possible to apply pattern recognition techniques to  $H$ , for example,

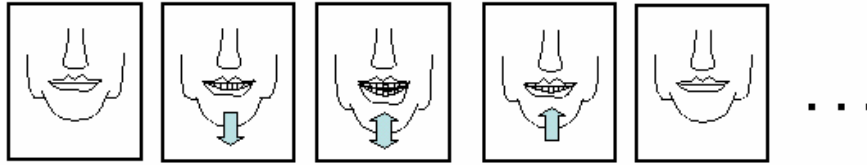
- Step 5.** *Cross-correlate* sequence from Step 1 with training set, to further examine and verify  $H$ .
- Step 6.** Refine  $H$  to identify: (a) chewing/non-chewing, (b) duration of motion, as well as (c) frequency of mandibular oscillation.

It is important to note that the output of the proposed algorithm would emphasize the three attributes (a-c) listed in Step 6, above. Initially, however, it will be necessary to develop a simpler algorithm, primarily using frequency-domain analysis, which will be summarized under separate cover. The following examples are illustrative of how we expect our eventual algorithm to function.

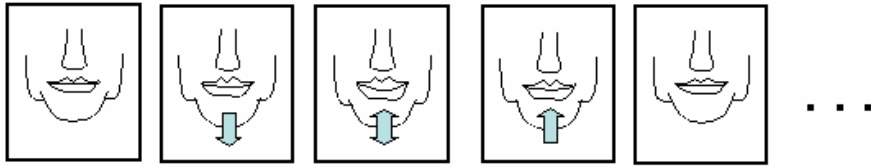
### 3.3. Illustrative Examples

The operation of the preceding algorithm, and the notion of classifying facial/jaw motion by dominant frequencies, is illustrated notionally in Figures 7 through 9.

- **Chewing with mouth partially open** (looks like talking)

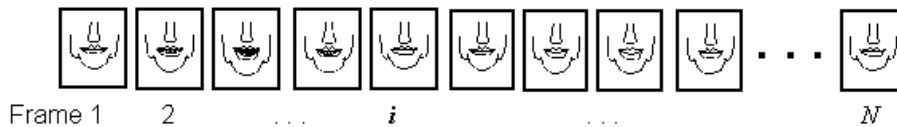


- **Chewing with mouth closed** (does not look like talking)



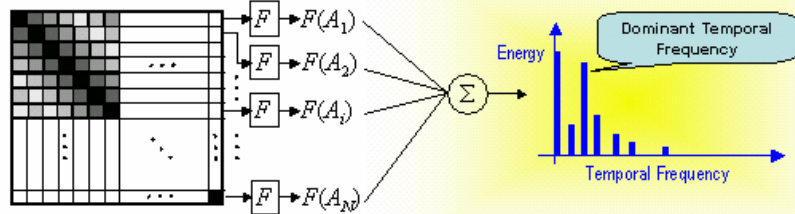
**Figure 7.** Notional diagram of chewing with mouth open (can be naively confused with talking), and chewing with mouth closed.

- 1) Given a video sequence of chewing imagery



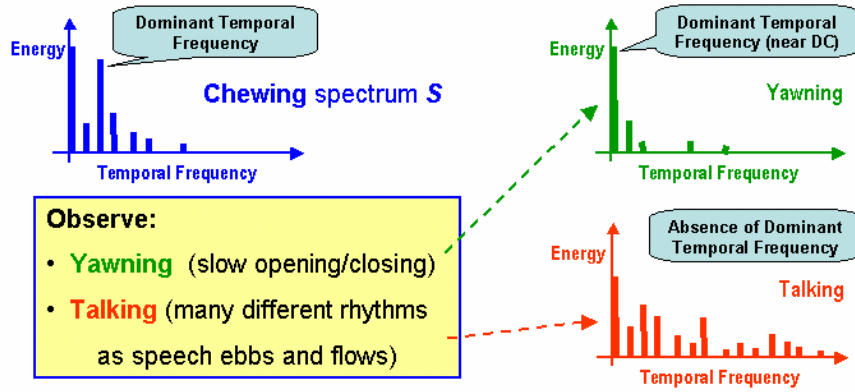
- 2) Form autocorrelation matrix  $A$

- 3) Average temporal spectrum



**Figure 8.** Simplified notional view of the facial/jaw motion quantification algorithm presented in Steps 1-4, above, which is based on technique presented in Cutler and Davis (1999). Here,  $F$  denotes the short-time Fourier transform. For purposes of generality,  $A$  could be either the similarity matrix or autocorrelation matrix (we plan to explore both, to investigate implementational efficiency).

- Given an averaged Fourier spectrum  $S$  of *chewing* video matrix  $A$
- What are differences between  $S$  and other oral or perioral behaviors?



**Figure 9.** Notional diagram of the spectral classification process, which would accept spectral quantification of various video sequences, to quantify and classify facial/jaw motion behaviors.

### 3.4. Key Challenges and Future Work

The key technical challenges involved in implementing the proposed algorithm include, but are not limited to:

- Acquisition of low-noise imagery, to increase reliability of the video data;
- Registration of video sequence frames in terms of object of interest in the scene (e.g., facial, jaw, and mouth structures);
- For processor(s) embedded in a sensor network, we must consider the complexity of computing the similarity matrix, as well as the autocorrelation matrix and its frequency analysis;
- Accuracy and reliability of spectral correlation, in the presence of possible input nonergodicities.

Object scaling and registration are well understood in the context of facial imagery. Human faces have four key points (centroid of nasal bridge, medial canthi of the eyes, and centroid of the nasal tip), which can be readily located in the type of video imagery proposed for this study. Computational procedures for location, scaling, and registration are freely available on the Internet, and have been published extensively in the literature.

Analysis of complexity pertaining to the Fourier transformation of an  $N \times N$  similarity or autocorrelation matrix is simply performed. If the Euclidean distance is applied to  $m \times n$ -pixel image pairs as a similarity measure, then  $\mathbf{O}(mn)$  multiplications and additions are required per similarity measure. The construction of the similarity matrix would require  $\mathbf{O}(N^2)$  similarity computations, so the cost of similarity matrix computation is  $\mathbf{O}(N^2mn)$ . In the context of row- or column-wise Fourier transformation shown in Figure 8,  $\mathbf{O}(N^2 \log N)$  complex multiplications and additions would be required. For video sequences of realistic length (e.g.,  $N < 1000$ ), this is not burdensome for modern embedded CPUs or digital signal processors. The comparison of  $K$  temporal spectra each having  $L$  frequency bands would require  $\mathbf{O}(K^2L)$  operations, which is not burdensome for small pattern sets (e.g.,  $K < 1000$  and  $L < 64$ ).

The accuracy and reliability of spectral correlation will depend upon three factors, none of which can be precisely estimated at this time. Firstly, the similarity of the temporal spectral will

dictate the degree of confusion which results from their comparison. Secondly, spectral noise levels and frequency resolution can adversely impact the performance of selected classifiers. Thus, emerging pattern classifiers that perform well in high noise and with partial information, such as morphological neural networks (Ritter, 1998) and tabular nearest-neighbor encoding (Key and Schmalz, 1999) will be investigated, and tested on data derived from our prototype algorithms applied to the initial dataset.

The proposed work will involve the following tasks:

- (1) *Acquire database of training and test imagery* - as noted previously, we propose to acquire four chewing video sequences, and several additional sequences containing yawning and talking imagery. The latter will be used to test the spectral discrimination algorithm.
- (2) *Develop and test algorithms for spectral analysis and comparison*, per the preceding presentation of our algorithm (Section 3.2).
- (3) *Analyze complexity and effectiveness of algorithms* – this is a crucial task for implementation of spectral analysis and comparison capabilities on embedded processors that might be found in wearable computers or communication devices. In particular, we propose to analyze the time and space complexity, together with power consumption, to support eventual design of wearable sensors.
- (4) *Comprehensive system test on entire test/training set* – following the initial data acquisition, we plan to acquire a comprehensive set of chewing video sequences, during the period of algorithm development and analysis. These sequences will be much longer than the initial video clips, and would contain different types of chewing behaviors (e.g., slow, fast, mouth open or closed). This database would provide a much more realistic test for our refined prototype algorithm.
- (5) *Explore feasibility of **fusing classifier results** with results of published techniques for auditory monitoring (e.g., chewing sounds)* – Given the discussion of different techniques for measuring chewing activity (Sections 1 and 2), we propose to investigate the possibility of using various data fusion algorithms to combine acoustic, EMG, and visual sensor data to form a more complete view of a given patient's chewing behavior. This could also be used in combination with caloric input models to monitor dietary behavior for obesity and diabetes studies.
- (6) *Explore additional modalities for monitoring chewing behaviors* – for example, infrared visual sensors to determine temperature of food on the plate, in the mouth, etc. Additionally, chemical sensors might be employed to detect telltale food fragrances (e.g., a patient is eating red meat when he should be enjoying a salad).

A further ongoing effort will emphasize searching the literature for new sensing modalities and fusion operators, to keep our research up-to-date with other research in health monitoring.

## 4. Bibliography

### Primary References:

- O. Amft, O., M. Stager, P. Lukowicz, and G. Troster (2005) Analysis of chewing sounds for dietary monitoring, *Proc. 7th Intl. Conf. On Ubiquitous Computing (Tokyo)*, pp. 65-72.
- Cutler, R. and L. Davis. (2000) Robust real-time periodic motion detection, analysis, and applications, *IEEE Tr. PAMI* **22**:781-796.
- Key, G., M.S. Schmalz, F.M. Caimi, and G.X. Ritter (1999) Performance analysis of tabular nearest neighbor encoding algorithm for joint compression and ATR, *Proceedings SPIE* **3814**:115-142 (1999).
- Nakamura, Y. and N. Katakura (1995) Generation of masticatory activity in the brainstem, *Neuroscience Research* **23**:1-19.
- Onozuka, M., M. Fujita, K. Watanabe, Y. Hirano, M. Niwa, K. Nishiyama, and S. Saito. Age-related changes in brain regional activity during chewing: A functional magnetic resonance imaging study, *J. Dental Research* **82**:657-660.
- G.X. Ritter, P. Sussner, and J.L. Diaz-de-Leon (1998) Morphological associative memories, *IEEE Transactions on Neural Networks* **9**:281-293.

### **Neurophysiological Basis** (from Nakamura et al. 1995)

- Appenteng, K., Conyers, L. and Moore, J.A. (1989) The monosynaptic excitatory connections of single trigeminal interneurons to the V motor nucleus of the rat. *J. Physiol.*, 417: 91-104.
- Appenteng, K., Conyers, L., Curtis, J. and Moore, J.A. (1990a) Monosynaptic connexions of single V interneurons to the contralateral V motor nucleus in anaesthetized rats. *Brain Res.*, 514: 128-130.
- Appenteng, K., Conyers, L., Curtis, J. and Moore, J.A. (1990b) Unitary monosynaptic EPSPs elicited by V interneurons in V motoneurons of anaesthetized rats. *J. Physiol.*, 427: 46P.
- Berrevoets, C.E. and Kuypers, H.G.J.M. (1975) Pericruciate cortical neurons projecting to brain stem reticular formation, dorsal column nuclei and spinal cord in cat. *Neurosci. Lett.*, 1: 257-262.
- Blom, S. (1960) Afferent influences on tongue muscle activity. A morphological and physiological study in the cat. *Acta Physiol. Scand.*, 49 (Suppl.170): 1-97.
- Bremer, F. (1923) Physiologic nerveuse de la mastication chez le chat et lapin. Reflexes de la mastication. R6ponses masticatrices corticales et centre cortical du gout. *Arch. Int. Physiol.*, 21: 308-352.
- Brodin, L. and Grillner, S. (1985) The role of putative excitatory amino acid neurotransmitters in the initiation of locomotion in the lamprey spinal cord. I. The effects of excitatory amino acid antagonists. *Brain Res.*, 360: 139-148.
- Brodin, L., Grillner, S. and Rovainen, C.M. (1985) NMDA, kainite and quisqualate receptors and the generation of fictive locomotion in the lamprey spinal cord. *Brain Res.*, 325: 302-306.
- Carli, G., Dietsch-Spiff, K. and Pompeiano, O. (1967) Mechanisms on muscle spindle excitation. *Arch. Ital. Biol.*, 105: 273-289.
- Carpenter, D.O. (1989) Central nervous system mechanisms in deglutition and emesis. In: J.D. Wood (Ed.), *Handbook of Physiology: The Gastrointestinal System. Motility and Circulation I*, American Physiological Society, Bethesda, pp. 685-714.

- Carpenter, M.B. and Hanna, G.R. (1961) Fiber projections from the spinal trigeminal nucleus in the cat. *J. Comp. Neurol.*, 117: 117-125.
- Catsman-Berrevoets, C.E. and Kuypers, H.G.J.M. (1976) Cells of origin of cortical projections to dorsal column nuclei, spinal cord and bulbar medial reticular formation in the rhesus monkey. *Neurosci. Lett.*, 3: 245-252.
- Cazalets, J.R., Sqalli-Houssaini, Y. and Clarac, F. (1992) Activation of the central pattern generators for locomotion by serotonin and excitatory amino acids in neonatal rat. *J. Physiol.*, 455: 187-204.
- Chandler, S.H. (1989) Evidence for excitatory amino acid transmission between mesencephalic nucleus of V afferents and jaw-closer motoneurons in the guinea pig. *Brain Res.*, 477: 252-264.
- Chandler, S.H. and Goldberg, L.J. (1981) Evidence for pattern generator control of the effects of spindle afferent input during rhythmical jaw movements. *Can. J. Physiol. Pharmacol.*, 59:707-712.
- Chandler, S.H. and Goldberg, L.J. (1982) Intracellular analysis of synaptic mechanisms controlling spontaneous and cortically induced jaw movements in the guinea pig. *J. Neurophysiol.*, 48:126-138.
- Chandler, S.H. and Goldberg, L.J. (1984) Differentiation of the neural pathways mediating cortically induced and dopaminergic activation of the central pattern generator (CPG) for rhythmical jaw movements in the anesthetized guinea pig. *Brain Res.*, 323:297-301.
- Chandler, S.H. and Tal, M. (1986) The effects of brain stem transactions on the neuronal networks responsible for rhythmical jaw muscle activity in the guinea pig. *J. Neurosci.*, 6: 1831-1842.
- Chandler, S.H. and Tal, M. (1987) Brain-stem perturbations during cortically evoked rhythmical jaw movements: effects of activation of brain-stem loci on jaw muscle cycle characteristics. *J. Neurosci.*, 7: 463-472.
- Chandler, S.H., Goldberg, L.J. and Alba, B. (1985a) Effects of a serotonin agonist and antagonist on cortically induced rhythmical jaw movements in the anesthetized guinea pig. *Brain Res.*, 334:201-206.
- Chandler, S.H., Goldberg, L.J. and Lambert, R.W. (1985b) The effects of orofacial input on spontaneously occurring and apomorphine-induced rhythmical jaw movements in the anesthetized guinea pig. *Neurosci. Lett.*, 53: 45-49.
- Chandler, S.H., Nielsen, S.A. and Goldberg, L.J. (1985c) The effects of a glycine antagonist (strychnine) on cortically induced rhythmical jaw movements in the anesthetized guinea pig. *Brain Res.*, 325: 181-186.
- Chandler, S.H., Turman, J., Jr., Salem, L. and Goldberg, L.J. (1990) The effects of nanoliter ejections of lidocaine into pontomedullary reticular formation on cortically induced rhythmical jaw movements in the guinea pig. *Brain Res.*, 256: 54-64.
- Clark, R.W. and Luschei, E.S. (1974) Short latency jaw movement produced by low intensity intracortical microstimulation of the precentral face area in monkeys. *Brain Res.*, 70: 144-147.
- Cody, F.W. and Richardson, H.C. (1978) Responses of cerebellar interpositus nuclear neurones to trigeminal inputs in the cat. *J. Physiol.*, 277: 62P-63P.

- Cody, F.W. and Richardson, H.C. (1979) Mossy and climbing fibre mediated responses evoked in the cerebellar cortex of the cat by trigeminal afferent stimulation. *J. Physiol.*, 287: 1-14.
- Darian-Smith, I. and Phillips, G. (1964) Secondary neurones within a trigemino-cerebellar projection to the anterior lobe of the cerebellum in the cat. *J. Physiol.*, 170: 53-68.
- Dean, P., Redgrave, P. and Eastwood, L. (1982) Suppression of apomorphine-induced oral stereotypy in rats by microinjection of muscimol into midbrain. *Life Sci.*, 30: 2171-2179.
- Dellow, P.G. and Lund, J.P. (1971) Evidence for central timing of rhythmical mastication. *J. Physiol.*, 215: 1-13.
- Deniau, J.M. and Chevalier, G. (1992) The lamellar organization of the rat substantia nigra pars reticulata: distribution of projection neurons. *Neuroscience*, 46: 361-377.
- Donga, R. and Lund, J.P. (1991) Discharge patterns of trigeminal commissural last-order interneurons during fictive mastication in the rabbit. *J. Neurophysiol.*, 66: 1564-1578.
- Donga, R., Lund, J.P. and Veilleux, D. (1990) An electrophysiological study of trigeminal commissural interneurons in the anesthetized rabbit. *Brain Res.*, 515: 351-354.
- Donga, R., Dubuc, R., Kolta, A. and Lund, J.P. (1992) Evidence that the masticatory muscles receive a direct innervation from cell group k in the rabbit. *Neuroscience*, 49: 951-961.
- Ehrmann, O., Mansour, R. and Jacquart, G. (1984) A micrometric and cytophotometric study of the simultaneous development of the cerebellar cortex and dental function in the rat during the early post-natal period. *Arch. Oral Biol.*, 29: 407-411.
- Enomoto, S., Katakura, N., Sunada, T., Katayama, T., Hirose, Y. and Nakamura, Y. (1985) Cortically induced masticatory rhythm in masseter motoneurons after blocking inhibition by strychnine and tetanus toxin. *Neurosci. Res.*, 4: 396-412.
- Enomoto, S., Schwartz, G. and Lund, J.P. (1987) The effects of cortical ablation on mastication in the rabbit. *Neurosci. Lett.*, 82:162-166.
- Enomoto, S., Kohase, H. and Nakamura, Y. (1995) Dual brainstem projection from the cortical masticatory area in guinea pig. *Neuroreport*, 6, in press.
- Fagg, G.E. and Foster, A.C. (1983) Amino acid neurotransmitters and their pathways in the mammalian central nervous system. *Neuroscience*, 4: 701-719.
- Feldman, J.L., Smith, J.C., McRimmon, D.R., Ellenberger, H.H. and Speck, D.F. (1988) Generation of respiratory pattern in mammals. In: A.H. Cohen, S. Rossignol and S. Grillner (Eds.), *Neural Control of Rhythmic Movements in Vertebrates*, John Wiley, New York, pp. 73-100.
- Fonnum, F. (1984) Glutamate: a neurotransmitter in mammalian brain. *J. Neurochem.*, 42: 1-11.
- Gerstner, G.E. and Goldberg, L.J. (1989) An analysis of mandibular movement trajectories and masticatory muscle EMG activity during drinking in the guinea pig. *Brain Res.*, 479: 6-15.
- Gerstner, G.E., Goldberg, L.J. and De Bruyne, K. (1989) Angiotensin II-induced rhythmic jaw movements in the ketamine-anesthetized guinea pig. *Brain Res.*, 478: 233-240.
- Goldberg, L.J. and Tal, M. (1978) Intracellular recording in trigeminal motoneurons of the anesthetized guinea pig during rhythmic jaw movements. *Exp. Neurol.*, 58:102-111.
- Goldberg, L.J., Chandler, S.H. and Tal, M. (1982) Relationship between jaw movements and trigeminal motoneuron membranepotential fluctuations during cortically induced rhythmical jaw movements in the guinea pig. *J. Neurophysiol.*, 48: 110-125.

- Grillner, S., McClellan, A., Sigvardt, K., Wall6n, P. and Wall6n, M. (1981) Activation of NMDA-receptors elicits "fictive locomotion" in lamprey spinal cord in vitro. *Acta Physiol. Scand.*, 113:549-551.
- Gurahian, S.M., Chandler, S.H. and Goldberg, L.J. (1989) Intracellular analysis of trigeminal motoneuron rhythmical activity during stimulation of pontomedullary reticular formation in anesthetized guinea pig. *J. Neurophysiol.*, 62: 1225-1236.
- Harada, Y., Kuno, M. and Wang, Y.Z. (1986) Differential effects of carbon dioxide and pH on central chemoreceptors in the rat in vitro. *J. Physiol.*, 368: 679-687.
- Harris-Warrick, R.M. (1988) Chemical modulation of central pattern generators. In: A.H. Cohen, S. Rossignol and S. Grillner (Eds.), *Neural Control of Rhythmic Movements in Vertebrates*, John Wiley, New York, pp. 285-331.
- Hashimoto, N., Katayama, T., Ishiwata, Y. and Nakamura, Y. (1989) Induction of rhythmic jaw movements by stimulation of the mesencephalic reticular formation in the guinea pig. *J. Neurosci.*, 9: 2887-2901.
- Hassler, R. and Muhs-Clement, K. (1964) Architektonischer Aufbau des sensorimotorischen und parietalen Cortex der Katze. *J. Hirnforsch.*, 6: 377-429.
- Hiiemae, K.M. (1978) Mammalian mastication: a review of the activity of the jaw muscles and the movements they produce in chewing. In: P.M. Butler and K.A. Joysey (Eds.), *Development, Function and Evolution of Teeth*, Academic Press, London, pp. 359-398.
- Hiraba, K., Taira, M., Sahara, Y. and Nakamura, Y. (1988) Singleunit activity in bulbar reticular formation during food ingestion in chronic cats. *J. Neurophysiol.*, 60: 1333-1349.
- Holstege, G. and Kuypers, H.G.J.M. (1977) Propriobulbar fibre connections to the trigeminal, facial and hypoglossal motor nuclei. I. An anterograde degeneration study in the cat. *Brain*, 100: 239-264.
- Holstege, G., Kuypers, H.G.J.M. and Dekker, J.J. (1977) The organization of the bulbar fibre connections to the trigeminal, facial and hypoglossal motor nuclei. If. An autoradiographic tracing study in the cat. *Brain*, 100: 265-286.
- Hosokawa, H. (1961) Proprioceptive innervation of striated muscle in the territory of the cranial nerves. *Texas Rep. Biol. Med.*, 19: 405-464.
- Inoue, T., Kato, T., Masuda, Y., Nakamura, T, Kawamura, Y. and Morimoto, T. (1989) Modifications of masticatory behavior after trigeminal deafferentation in the rabbit. *Exp. Brain Res.*, 74: 579-591.
- Inoue, T., Masuda, Y., Nagashima, T., Yoshikawa, K. and Morimoto, T. (1992) Properties of rhythmically active neurons around the trigeminal motor nucleus during fictive mastication in the rat. *Neurosci. Res.*, 14: 275-294.
- Inoue, T., Chandler, S.H. and Goldberg, L.J. (1994) Neuropharmacological mechanisms underlying rhythmical discharge in trigeminal interneurons during fictive mastication. *J. Neurophysiol.*, 71: 2061-2073.
- Iriki, A. and Nakamura, Y. (1987) Reorganization of corticobulbar projections corresponding to the development of feeding behavior from sucking to chewing in guinea pigs. *Neurosci. Res.*, Suppl., 5: \$61.
- Iriki, A., Nozaki, S. and Nakamura, Y. (1988) Feeding behavior in mammals: corticobulbar projection is reorganized during conversion from sucking to chewing. *Brain Res.*, 44: 189-196.

- Jacquart, G., Mahler, P. and Kachani-Mansour, R. (1986) Growth of trigemino-cerebellar areas in infant rat studied by micrometric and cytophotometric methods. *Arch. Oral Biol.*, 31: 573-576.
- Jones, B.E. and Yang, T.Z. (1985) The efferent projections from the reticular formation and the locus coeruleus studied by anterograde and retrograde axonal transport in the rat. *J. Comp. Neurol.*, 242: 56-92.
- Juch, P.J.W., Van Willigen, J.D., Broekhuojen, M.L. and Ballantijn, C.M. (1985) Peripheral influences on the central pattern-rhythm generator for tongue movements in the rat. *Arch. Oral Biol.*, 30: 415-421.
- Katakura, N. and Chandler, S.H. (1990) An iontophoretic analysis of the pharmacologic mechanisms responsible for trigeminal motoneuronal discharge during masticatory-like activity in the guinea pig. *J. Neurophysiol.*, 63: 356-369.
- Katakura, N. and Chandler, S.H. (1991) Iontophoretic analysis of the pharmacologic mechanisms responsible for initiation and modulation of trigeminal motoneuronal discharge evoked by intra-oral afferent stimulation. *Brain Res.*, 549: 66-77.
- Katakura, N. and Nakamura, Y. (1995) Sucking-like activity in in-vitro brainstem preparation from newborn rat. *J. Dent. Res.*, 74, 513.
- Katakura, N., Lia, J. and Nakamura, Y. (1994) NMDA-induced rhythmical activities of the hypoglossal motoneurons in an in vitro brainstem-spinal cord preparation from newborn rats. *Neurosci. Res.*, Suppl., 19: S176.
- Katakura, N., Lia, J. and Nakamura, Y. (1995a) NMDA-induced rhythmical activity in XII nerve of isolated CNS from newborn rats. *Neuroreport*, 6: 601-604.
- Katakura, N., Lia, J. and Nakamura, Y. (1995b) Separate oscillators for NMDA-induced rhythmical hypoglossal nerve activities in both halves of the brainstem in an in vitro preparation from newborn rats. Fourth IBRO World Congress of Neuroscience Abstracts, in press.
- Katayama, T., Hashimoto, N., Ishiwata, Y., Ono, T. and Nakamura, Y. (1992) Control of trigeminal motoneurons from the cerebellar interpositus nucleus of the guinea pig. *J. Neurophysiol.*, 67: 1528-1542.
- Katayama, T., Kohase, H. and Nakamura, Y. (1993) Resetting of cortically induced rhythmical jaw movements by stimulation of the cerebellar interpositus nucleus in the guinea pig. *Brain Res.*, 617: 143-146.
- Katoh, M., Taira, M., Katakura, N. and Nakamura, Y. (1982) Cortically induced effects on trigeminal motoneurons after transection of the brain stem at the pontobulbar junction of the cat. *Neurosci. Lett.*, 33: 141-146.
- Kawamura, Y. and Tsukamoto, S. (1960) Analysis of jaw movements from the cortical jaw motor area and amygdala. *Jpn. J. Physiol.*, 10: 471-488.
- Kessler, J.P., Cherkaoui, N., Catalin, D. and Jean, A. (1990) Swallowing responses induced by microinjection of glutamate and glutamate agonists into the nucleus tractus solitarius of ketamine-anaesthetized rats. *Exp. Brain Res.*, 83: 151-158.
- Kubo, Y., Enomoto, S. and Nakamura, Y. (1981) Synaptic basis of cortically induced rhythmical masticatory activity of trigeminal motoneurons in immobilized cats. *Brain Res.*, 230:97-110.

- Kubota, K., Narita, N., Takada, K., Lee, M.-S., Shibantai, S. and Nagae, K. (1988) Origin of lingual proprioceptive afferents in Japanese monkey, *M. fuscata fuscata*, studied by HRP-labeling technique. *Anat. Anz.*, 166: 141-148.
- Kudo, N. and Yamada, T. (1987) N-Methyl-D,L-aspartate-induced locomotor activity in a spinal cord-hindlimb muscles preparation of the newborn rat studied in vitro. *Neurosci. Lett.*, 75: 43-48.
- Kudo, N., Ozaki, S. and Yamada, Y. (1991) Ontogeny of rhythmic activity in the spinal cord of the rat. In: M. Shimamura, S. Grillner and V.R. Edgerton (Eds.), *Neurobiological Basis of Human Locomotion*, Japan Scientific Societies Press, Tokyo, pp. 127-136.
- Kurasawa, I., Hirose, Y., Sunada, T. and Nakamura, Y. (1988) Phaselinked modulation of excitability of presynaptic terminals of lowthreshold afferent fibers in the inferior alveolar nerve during cortically induced fictive mastication in the guinea pig. *Brain Res.*, 446: 113-120.
- Kurasawa, I., Toda, K. and Nakamura, Y. (1990) Non-reciprocal facilitation of trigeminal motoneurons innervating jaw-closing and jaw-opening muscles induced by iontophoretic application of serotonin in the guinea pig. *Brain Res.*, 515: 126-134.
- Kuypers, H.G.J.M. (1958) Some projections from the peri-central cortex to the pons and lower brain stem in monkey and chimpanzee. *J. Comp. Neurol.*, 110: 221-255.
- Kuypers, H.G.J.M. (1960) Central cortical projections to motor and somato-sensory cell groups. An experimental study in the rhesus monkey. *Brain*, 83: 161-184.
- Kuypers, H.G.J.M. (1981) Anatomy of descending pathways. In: V.B. Brooks (Ed.), *Handbook of Physiology. Section 1: The Nervous System, Vol. II. Motor control, Part 1*, American Physiological Society, Bethesda MD, pp. 597-666.
- Kuypers, H.G.J.M. and Lawrence, D.G. (1967) Cortical projections to the red nucleus and the brain stem in the rhesus monkey. *Brain Res.*, 4: 151-188.
- Lambert, R.W., Goldberg, L.J. and Chandler, S.H. (1986) Comparison of mandibular movement trajectories and associated patterns of oral muscle electromyographic activity during spontaneous and apomorphine-induced rhythmic jaw movements in the guinea pig. *J. Neurophysiol.*, 55: 301-319.
- Landgren, S., Olsson, K. and Westberg, K.G. (1986) Butbar neurons with axonal projections to the trigeminal motor nucleus in the cat. *Exp. Brain Res.*, 65:98-111.
- Law, M.E. (1954) Lingual proprioception in pig, dog and cat. *Nature*, 174: 1107-1108.
- Liu, Z.J., Masuda, Y., Inoue, T., Fuchihata, H., Sumida, A., Takada, A. and Morimoto, T. (1993) Coordination of cortically induced rhythmical jaw and tongue movements in the rabbit. *J. Neurophysiol.*, 69: 569-584.
- Lund, J.P. (1991) Mastication and its control by the brain stem. *Crit. Rev. Oral Biol. Med.*, 2: 33-64.
- Lund, J.P. and Dellow, P.G. (1971) The influence of interactive stimuli on rhythmical masticatory movements in rabbits. *Arch. Oral Biol.*, 16: 215-223.
- Lund, J.P. and Lamarre, Y. (1974) Activity of neurons in the lower precentral cortex during voluntary and rhythmical jaw movements in the monkey. *Exp. Brain Res.*, 19: 282-299.
- Lund, J.P. and Olsson, K.A. (1983) The importance of reflexes and their control during jaw movement. *TINS*, 6: 458-463.

- Lurid, J.P., Rossignol, S. and Murakami, T. (1981) Interactions between the jaw-opening reflex and mastication. *Can. J. Physiol. Pharmacol.*, 59: 683-690.
- Lund, J.P., Enomoto, S., Hayashi, H., Hiraba, K., Katoh, M., Nakamura, Y., Sahara, Y. and Taira, M. (1983) Phase-linked variations in the amplitude of the digastric nerve jaw-opening reflex response during fictive mastication in the rabbit. *Can. J. Physiol. Pharmacol.*, 61:1122-1128.
- Lund, J.P., Sasamoto, K., Murakami, T. and Olsson, K.A. (1984) Analysis of rhythmical jaw movements produced by electrical stimulation of motor-sensory cortex of rabbits. *J. Neurophysiol.*, 52:1014-1029.
- Magoun, H.M., Ranson, S.W. and Fisher, C. (1933) Corticofugal pathways for mastication, lapping and other motor function in the cats. *Arch. Neurol. Psychiat. (Chicago)*, 30: 292-308.
- Marini, G. and Stogiu, L. (1985) Single unit activity in lateral reticular nucleus during cortically evoked masticatory movements in rabbits. *Brain Res.*, 337: 287-292.
- Miles, T.S. and Wiesendanger, M. (1975a) Organization of climbing fibre projections to the cerebellar cortex from trigeminal cutaneous afferents and from the SI face area of the cerebral cortex in the cat. *J. Physiol.*, 245: 409-424.
- Miles, T.S. and Wiesendanger, M. (1975b) Climbing fibre inputs to cerebellar Purkinje cells from trigeminal cutaneous afferents and the SI face area of the cerebral cortex in the cat. *J. Physiol.*, 245: 425-445.
- Miles, T.S., Cooke, J.D. and Wiesendanger, M. (1974) Localization in the cerebellar hemisphere of climbing-fiber responses evoked from the trigeminal nerve in the cat. *Can. J. Physiol. Pharmacol.*, 52: 1147-1153.
- Mizuno, N., Sauerland, E.K. and Clemente, C.D. (1968) Projections from the orbital gyrus in the cat. I. To brain stem structures. *J. Comp. Neurol.*, 133: 463-476.
- Mizuno, N., Konishi, A. and Sato, M. (1975) Localization of masticatory motoneurons in the cat and rat by means of retrograde axonal transport of horseradish peroxidase. *J. Comp. Neurol.*, 164:105-116.
- Mizuno, N., Yasui, Y., Nomura, S., Itoh, K., Konishi, A., Takeda, M. and Kudo, M. (1983) A light and electron microscopic study of premotor neurons for the trigeminal motor nucleus. *J. Comp. Neurol.*, 215: 290-298.
- Mora, F., Mogenson, G.J. and Rolls, E.T. (1977) Activity of neurons in the region of the substantia nigra during feeding in the monkey. *Brain Res.*, 133: 267-276.
- Morimoto, T. and Kawamura, Y. (1973) Properties of tongue and jaw movements elicited by stimulation of the orbital gyrus in the cat. *Arch. Oral Biol.*, 18: 361-372.
- Morimoto, T., Inoue, T., Masuda, Y. and Nagashima, T. (1989) Sensory component facilitating jaw-closing muscle activities in the rabbit. *Exp. Brain Res.*, 76: 424-440.
- Moriyama, Y. (1987) Rhythmical jaw movements and lateral medullary reticular formation in rats. *Comp. Biochem. Physiol. A*, 86: 7-14.
- Murakami, T., Lund, J.P. and Beaulieu, M. (1980) Elaboration and modification of patterns of rhythmical mastication. In: K. Kubota, Y. Nakamura and G.-H. Schumacher (Eds.), *Jaw Movement and Jaw Position*, VEB Verlag Volk und Gesundheit, Berlin, pp. 305-308.

- Nakamura, Y. and Kubo, Y. (1978) Masticatory rhythm in intracellular potential of trigeminal motoneurons induced by stimulation of orbital cortex and amygdala in cats. *Brain Res.*, 148: 504-509.
- Nakamura, Y., Goldberg, L.J. and Clemente, C.D. (1967) Nature of suppression of the masseteric monosynaptic reflex induced by stimulation of the orbital gyrus of cat. *Brain Res.*, 6: 184-198.
- Nakamura, Y., Kubo, Y., Nozaki, S. and Takatori, M. (1976) Cortically induced masticatory rhythm and its modification by tonic peripheral inputs in immobilized cats. *Bull. Tokyo Med. Dent. Univ.*, 23: 101-107.
- Nakamura, Y., Katoh, M., Enomoto, S. and Hiraba, K. (1982) Neural pathway involved in the excitation of motoneurons to jawopening muscles by stimulation of the orbital cerebral cortex in the cat. *Arch. Oral Biol.*, 27: 283-287.
- Nakamura, S., Muramatsu, S. and Yoshida, M. (1990) Role of the basal ganglia in manifestation of rhythmical jaw movement in rats. *Brain Res.*, 335-338.
- Nozaki, S., Iriki, A. and Nakamura, Y. (1986a) Localization of central rhythm generator involved in cortically induced rhythmical masticatory jaw-opening movement in the guinea pig. *J. Neurophysiol.*, 55: 806-825.
- Nozaki, S., Iriki, A. and Nakamura, Y. (1986b) Role of corticobulbar projection neurons in cortically induced rhythmical masticatory jaw-opening movement in the guinea pig. *J. Neurophysiol.*, 55: 826-845.
- Nozaki, S., Iriki, A. and Nakamura, Y. (1991) Brainstem commissural systems for bilateral synchronization of rhythmical jaw muscle activity induced by stimulation of the cortical masticatory area in the guinea pig. *Dent. Jpn.*, 28: 39-43.
- Nozaki, S., Iriki, A. and Nakamura, Y. (1993) Trigeminal premotor neurons in the bulbar parvocellular reticular formation participating in induction of rhythmical activity of trigeminal motoneurons by repetitive stimulation of the cerebral cortex in the guinea pig. *J. Neurophysiol.*, 69: 595-608.
- Olsson, K.A. and Westberg, K.-G. (1989) Interneurons in the trigeminal motor system. In: D. van Steenberghe and A. DeLaat (Eds.) *EMG of Jaw Reflexes in Man*. Leuven University Press, Leuven, pp. 19-50.
- Olsson, K.A. and Westberg, K.-G. (1991) Integration in trigeminal premotor interneurons in the cat. 2. Functional characteristics of neurones in the subnucleus-3, of the oral nucleus of the spinal trigeminal tract with a projection to the digastric motoneurone subnucleus. *Exp. Brain Res.*, 84:115-124.
- Olsson, K.A., Sasamoto, K. and Lund, J.P. (1986) Modulation of transmission in rostral trigeminal sensory nuclei during chewing. *J. Neurophysiol.*, 55: 56-75.
- Onimaru, H. (1995) Studies of the respiratory center using isolated brainstem-spinal cord preparations. *Neurosci. Res.*, 21: 183-190.
- Onimaru, H., Arata, A. and Homma, I. (1987) Localization of respiratory rhythm-generating neurons in the medulla of brainstem-spinal cord preparations from newborn rats. *Neurosci. Lett.*, 78:151-155.
- Poon, M. (1980) Induction of swimming in lamprey by L-DOPA and amino acids. *J. Comp. Physiol.*, 136: 337-344.

- Redgrave, P., Marrow, L. and Dean, P. (1992) Topographic organization of the nigrotectal projection in rat: evidence for segregated channels. *Neuroscience*, 50: 571-595.
- Richardson, H.C., Cody, F.W.L., Paul, V.E. and Thomas, A.G. (1978) Convergence of trigeminal and limb inputs onto cerebellar interpositus nuclear neurons in the cat. *Brain Res.*, 156: 355-359.
- Rossignol, S. and Dubuc, R. (1994) Spinal pattern generation. *Curr. Opin. Neurobiol.*, 4: 894-902.
- Sahara, Y., Hashimoto, N., Kato, M. and Nakamura, Y. (1988) Synaptic bases of cortically-induced rhythmical hypoglossal motoneuronal activity in the cat. *Neurosci. Res.*, 5: 439-452.
- Sasamoto, K., Zhang, G. and Iwasaki, M. (1990) Two types of rhythmical jaw movements evoked by stimulation of the rat cortex. *Jpn. J. Physiol.*, 32: 57-68.
- Schneider, J.S. (1987) Ingestion-related activity of caudate and entopeduncular neurons in the cat. *Exp. Neurol.*, 95: 216-223.
- Schwartz, G., Enomoto, S., Valiquette, C. and Lund, J.P. (1989) Mastication in the rabbit: a description of movement and muscle activity. *J. Neurophysiol.*, 62: 273-287.
- Smith, J.C. and Feldman, J.L. (1987) In vitro brainstem-spinal cord preparations for study of motor systems for mammalian respiration and locomotion. *J. Neurosci. Methods*, 21: 321-333.
- Smith, J.C., Feldman, J.L. and Schmidt, B.J. (1988) Neural mechanisms generating locomotion studied in mammalian brain stem-spinal cord in vitro. *FASEB J.*, 2: 2283-2288.
- Somana, R., Kotchabhadki, N. and Walberg, F. (1980) Cerebellar afferents from trigeminal sensory nuclei in the cat. *Exp. Brain Res.*, 38: 57-64.
- Sumi, T. (1969) Some properties of cortically-induced swallowing and chewing in rabbits. *Brain Res.*, 15: 107-120.
- Suzue, T. (1984) Respiratory rhythm generation in the in vitro brain stem-spinal cord preparation of the neonatal rat. *J. Physiol.*, 354: 183-183.
- Taylor, A. and Elias, S.A. (1984) Interaction of periodontal and jaw elevator spindle afferents in the cerebellum-sensory calibration. *Brain Behav. Evol.*, 25: 157-165.
- Ter Horst, G.J., Copray, J.C.V.M., Liem, R.S.B. and Van Willigen, J.D. (1991) Projections from the rostral parvocellular reticular formation to pontine and medullary nuclei in the rat: involvement in autonomic regulation and orofacial motor control. *Neuroscience*, 40: 735-758.
- Thach, W.T., Perry, J.G. and Schieber, M.H. (1982) Cerebellar output: body maps and muscle spindles. *Exp. Brain Res.*, Suppl., 6: 440-454.
- Thexton, A.J. (1973) Oral reflexes elicited by mechanical stimulation of palatal mucosa in the cat. *Arch. Oral Biol.*, 18: 971-980.
- Thexton, A.J., Hiiemae, K.M. and Crompton, A.W. (1980) Food consistency and bite size as regulators of jaw movement during feeding in the cat. *J. Neurophysiol.*, 44: 456-474.
- Travers, J.B. and Norgren, R. (1983) Afferent projections to the oral motor nuclei in the rat. *J. Comp. Neurol.*, 220: 280-298.
- Van Willigen, J.D. and Weijs-Boot, J. (1984) Phasic and rhythmic responses of the oral musculature to mechanical stimulation of the rat palate. *Arch. Oral Biol.*, 29:7-11.

- Vogt, C. and Vogt, O. (1926) Die vergleichend-architektonische und die vergleichend-reizphysiologische Felderung der Grosshirnrinde unter besonderer Berücksichtigung der menschlichen. *Naturwissenschaften*, 14: 1190-1194.
- Vornov, J.J. and Sutin, J. (1983) Brain stem projections to the normal and noradrenergically hyperinnervated trigeminal motor nucleus. *J. Comp. Neurol.*, 214: 198-208.
- Walton, K. and Llinas, R. (1985) An isolated in vitro preparation of the neonatal rat brain stem and spinal cord. *Soc. Neurosci. Abstr.*, 11: 24.
- Westberg, K.-G. and Olsson, K.A. (1991) Integration in trigeminal premotor interneurons in the cat. 1. Functional characteristics of neurons in the subnucleus-3, of the oral nucleus of the spinal trigeminal tract. *Exp. Brain Res.*, 84: 102-114.
- Westneat, M.W. and Hall, W.G. (1992) Ontogeny of feeding motor patterns in infant rats: an electromyographic analysis of suckling and chewing. *Behav. Neurosci.*, 106: 539-554.
- Wold, J.E. and Brodal, A. (1974) The cortical projection of the orbital and proreate gyri to the sensory trigeminal nuclei in the cat. An experimental anatomical study. *Brain Res.*, 65: 381-395.
- Woolston, D.C., Kassel, J. and Gibson, J.M. (1981) Trigemincerebellar mossy fibre branching to granule cell layer patches in the rat cerebellum. *Brain Res.*, 209: 255-269.
- Yasui, Y., Itoh, K., Takada, M., Mitani, A., Kaneko, T. and Mizuno, N. (1985) Direct cortical projections to the parabrachial nucleus in the cat. *J. Comp. Neurol.*, 234: 77-86.
- Yasui, Y., Tsumori, T., Ando, A., Domoto, T., Kayahara, T. and Nakano, K. (1994) Descending projections from the superior colliculus to the reticular formation around the motor trigeminal nucleus and the parvicellular reticular formation of the medulla oblongata in the rat. *Brain Res.*, 656: 420-426.
- Yoshida, A., Yasuda, K., Dostrovsky, J.O., Yong, C.B., Takemura, M., Shigenaga, T. and Sessle, B.J. (1994) Two major types of premotoneurons in the feline trigeminal nucleus oralis as demonstrated by intracellular staining with horseradish peroxidase. *J. Comp. Neurol.*, 347: 495-514.
- Zhang, G. and Sasamoto, K. (1990) Projection of two separate cortical areas for rhythmical jaw movements in the cat. *Brain Res. Bull.*, 24: 221-230.

#### **Age-Related Changes in Brain Response to Chewing Behaviors (from Onozuka et al. 2003)**

- Amaral DG, Witter MP (1989). The three-dimensional organization of the hippocampal formation: a review of anatomical data. *Neuroscience* 31:571-591.
- Friston KL, Holmes AP, Worsley KP, Poline JP, Frith CD, Frackowiak RSJ (1995). Statistical parametric maps in functional imaging: a general linear approach. *Hum Brain Mapp* 2:189-210.
- Godde B, Berkefeld T, David-Jurgens M, Dinse HR (2002). Age-related changes in primary somatosensory cortex of rats: evidence for parallel degenerative and plastic-adaptive processes. *Neurosci Biobehav Rev* 26:743-752.
- Grady CL, Furey ML, Pietrini P, Horwitz B, Rapoport SI. (2001a). Altered brain functional connectivity and impaired short-term memory in Alzheimer's disease. *Brain* 124:739-756.

- Grady CL, McIntosh AR, Beig S, Craik FI (2001b). An examination of the effects of stimulus type, encoding task, and functional connectivity on the role of right prefrontal cortex in recognition memory. *Neuroimage* 14:556-571.
- Grady CL, McIntosh AR, Beig S, Keightley ML, Burian HB, Black SE (2003). Evidence from functional neuroimaging of a compensatory prefrontal network in Alzheimer's disease. *J Neurosci* 23:986-993.
- Kemsley EK, Defernez M, Sprunt JC, Smith AC (2003). Electromyographic responses to prescribed mastication. *J Electromyogr Kinesiol* 13:197-207.
- Lutz K, Specht K, Shah NJ, Jäncke L (2000). Tapping movements according to regular and irregular visual timing signals investigated with fMRI. *NeuroReport* 11:1301-1306.
- Mazziotta RP, Cherry JC (1993). MRI-PET registration with automated algorithm. *J Comp Assist Tomog* 17:536-546.
- Meisenzahl EM, Schlosser R (2001). Functional magnetic resonance imaging research in psychiatry. *Neuroimaging Clin N Am* 11:365-374.
- Momose I, Nishikawa J, Watanabe T, Sasaki Y, Senda M, Kubota K, *et al.* (1997). Effect of mastication on regional cerebral blood flow in humans examined by positron-emission tomography with <sup>15</sup>Olabelled water and magnetic resonance imaging. *Arch Oral Biol* 42:57-61.
- Nakamura Y, Katakura N (1995). Generation of masticatory rhythm in the brainstem. *Neurosci Res* 23:1-19.
- Nakata M (1998). Masticatory function and its effects on general health. *Int Dent J* 48:540-548.
- Ogawa S, Tank DW, Menon R, Ellermann JM, Kim SG, Merkle H, *et al.* (1992). Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging. *Proc Natl Acad Sci USA* 89:5951-5955.
- Okimoto K, Ieiri K, Matsuo K, Terada Y (1991). Ageing and mastication: the relationship between oral status and the progress of dementia at senile hospital. *J Jpn Prosthodont Soc* 35:931-943.
- Onozuka M, Fujita M, Watanabe K, Hirano Y, Niwa M, Nishiyama K, *et al.* (2002). Mapping brain region activity during chewing: a functional magnetic resonance imaging study. *J Dent Res* 81:743-746.
- Pulvermuller F (1999). Words in the brain's language. *Behav Brain Sci* 22:253-336.
- Sesay M, Tanaka A, Ueno Y, Lecaroz P, De Beaufort DG (2000). Assessment of regional cerebral blood flow by xenon-enhanced computed tomography during mastication in humans. *Keio J Med* 49(Suppl 1): A125-A128.
- Squire LR, Zola-Morgan S (1991). The medial temporal lobe memory system. *Science* 253:1380-1386.
- Suzuki M, Ishiyama I, Takiguchi T, Ishikawa H, Suzuki Y, Sato Y. (1994). Effects of gum hardness on the response of common carotid blood flow volume, oxygen uptake, heart rate and blood pressure to gum-chewing. *J Mastica Health Sci* 4:9-20.
- Talairach J, Tournoux P (1988). Co-planar stereotaxic atlas of the human brain. New York: Thieme.
- Witter MP, van Hoesen GW, Amaral DG (1989). Topographical organization of the entorhinal projection to the dentate gyrus of the monkey. *J Neurosci* 9:216-228.

Yancey SW, Phelps EA (2001). Functional neuroimaging and episodic memory: a perspective. *J Clin Exp Neuropsychol* 23:32-48.

**Periodic Motion Detection:** (from Cutler and Davis, 1999)

- M. Allmen. *Image sequence description using spatiotemporal flow curves: Toward Motion-Based Recognition*. PhD thesis, University of Wisconsin, Madison, 1991.
- D. H. Ballard and M. J. Swain. Color indexing. *Int. Journal of Computer Vision*, 7-1:11–32, 1991.
- P. Brockwell and R. Davis. *Time Series: Theory and Methods*. Springer-Verlag, 1987.
- M. Casdagli. Recurrence plots revisited. *Physica D*, 108:12–44, 1997.
- C. J. Cohen, L. Conway, and D. Koditschek. Dynamic system representation, generation, and recognition of basic oscillatory motion gestures. In *IEEE International Conference on Automatic Face and Gesture Recognition*, 1996.
- R. Cutler and L. Davis. View-based detection and analysis of periodic motion. In *International Conference on Pattern Recognition*, page SA14, Brisbane, Australia, August 1998.
- R. Cutler and L. Davis. Real-time periodic motion detection, analysis, and applications. In *Proceedings of the Computer Vision and Pattern Recognition*, pages 326–332, Fort Collins, Colorado, June 1999.
- P. Eckmann, S. O. Kamphorst, and D. Ruelle. Recurrence plots of dynamical systems. *J. of Europhysics Letters*, 4:973–977, 1987.
- J. Emmerton. The pigeon's discrimination of movement patterns (lissajous figures) and contour-dependent rotational invariance. *Perception*, 15(5):573–588, 1986.
- H. Fujiyoshi and A. Lipton. Real-time human motion analysis by image skeletonization. In *IEEE Workshop on Applications of Computer Vision*, page Session 1A, October 1998.
- N. Goddard. The interpretation of visual motion: recognizing moving light displays. In *Proc. IEEE Workshop on Motion*, pages 212–220, March 1989.
- M. Hansen, P. Anandan, K. Dana, G. van der Wal, and P. Burt. Real-time scene stabilization and mosaic construction. In *DARPA Image Understanding Workshop*, pages 457–465, Monterrey, CA, Nov. 1994.
- L. Haritaoglu, R. Cutler, D. Harwood, and L. Davis. Backpack: Detection of people carrying objects using silhouettes. In *International Conference on Computer Vision*, pages 102–107, 1999.
- B. Heisele and C. Wohler. Motion-based recognition of pedestrians. In *International Conference on Pattern Recognition*, August 1998.
- P.L. Houtekamer, H.L. Mitchell, G. Pellerin, M. Buehner, M. Charron, L. Spacek, and B. Hansen. Atmospheric data assimilation with an Ensemble Kalman Filter: Results with real observations. *Monthly Weather Review*, pages 604–620, 2005.
- D. Huttenlocher, G. A. Klanderman, and W. Rucklidge. Comparing images using the hausdorff distance. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 15(9):805–863, 1993.
- G. Johansson. Visual motion perception. *Scientific American*, (232):75–88, June 1976.
- R. Kern. Visual position stabilization in the hummingbird hawk moth, *Macroglossum stellatarum* L. I. Behavioural analysis. *J Comp Physiol [A]*, 182(2):225–237, 1998.

- J. P. Lewis. Fast normalized cross-correlation. In *Vision Interface*, 1995.
- H.-C. Lin, L.-L. Wang, and S.-N. Yang. Extracting periodicity of a regular texture based on autocorrelation functions. *Pattern Recognition Letters*, 18:433–443, 1997.
- J. Little and J. Boyd. Recognizing people by their gait: the shape of motion. *Videre*, 1(2), 1998.
- F. Liu and R. Picard. Finding periodicity in space and time. *International Conference on Computer Vision*, pages 376–383, January 1998.
- J. Marion. *Classical dynamics of particles and systems*. Academic Press, 1970.
- G. McGuire, N. B. Azar, and M. Shelhamer. Recurrence matrices and the preservation of dynamical properties. *Phys. Lett. A*, 237:43–47, 1997.
- T. A. McMahon. *Muscles, Reflexes, and Locomotion*. Princeton University Press, 1984.
- D. McReynolds and D. Lowe. Rigidity checking of 3D point correspondences under perspective projection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 18(12):1174–1185, 1996.
- S. Niyogi and E. Adelson. Analyzing and recognizing walking figures in xyt. In *Proceedings of the Computer Vision and Pattern Recognition*, pages 469–474, 1994.
- S. Niyogi and E. Adelson. Analyzing gait with spatiotemporal surfaces. In *IEEE Workshop on Motion of Non-Rigid and Articulated Objects*, pages 64–69, Austin, Texas, 1994.
- A. Oppenheim and R. Schaffer. *Discrete-time signal processing*. Prentice-Hall, 1989.
- D. B. Percival. *Spectral Analysis for Physical Applications: Multitaper and Conventional Univariate Techniques*, chapter Harmonic Analysis. Cambridge University Press, 1993.
- R. Polana and R. Nelson. Detection and recognition of periodic, non-rigid motion. *International Journal of Computer Vision*, 23(3):261–282, June/July 1997.
- W. Press, S. Teukolsky, W. Vetterling, and B. Flannery. *Numerical Recipes in C*. Cambridge University Press, 1988.
- D. Schumacher. General filtered image rescaling. In D. Kirk, editor, *Graphics Gems III*. Harcourt Brace Jovanovich, 1992.
- S. M. Seitz and C. R. Dyer. View-invariant analysis of cyclic motion. *International Journal of Computer Vision*, 25(3):1–23, 1997.
- A. Selinger and L. Wixson. Classifying moving objects as rigid or non-rigid without correspondences. In *DARPA Image Understanding Workshop*, pages 341–347, November 1998.
- P. Tsai, M. Shah, K. Keiter, and T. Kasparis. Cyclic motion detection for motion based recognition. *Pattern Recognition*, 27(12):1591–1603, 1994.
- H. Weyl. *Symmetry*. Princeton University Press, 1952.
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