7 to 12 Hz Activity in Rat Gustatory Cortex Reflects Disengagement From a Fluid Self-Administration Task

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Fontanini, Alfredo and Donald B. Katz. 7 to 12 Hz activity in rat gustatory cortex reflects disengagement from a fluid self-administration task. J Neurophysiol 93: 2832–2840, 2005; doi:10.1152/jn.01035.2004. The 7 to 12 Hz rhythm is a high-voltage oscillatory phenomenon recorded in many rat neocortical regions, largely analogous to the rodent and human somatosensory μ rhythm. Central to any interpretation of the functional significance of this pattern is the analysis of the behavioral context associated with it. Much of the debate on the function of μ, variously believed to represent either an environment-oriented or -isolated state, has relied primarily on its association with quiet immobility. In this report, we describe the relationship between the 7 to 12 Hz rhythm and a more complex behavioral setting, in which we were able to dissociate task orientation from disengagement. We trained head-restrained, water-restricted rats to perform a simple variant of a timed fluid self-administration task, while recording local field potentials from gustatory cortex (GC). Rats progressed through two behavioral states that were clearly distinguishable on the basis of lever-pressing regimes: a task-oriented state and a second state that reflected disengagement from the task. Concurrent GC neural recordings revealed bilaterally coherent oscillations in the 7 to 12 Hz range associated solely with the latter state. Consistent with published recordings of μ rhythm from somatosensory cortex, these rhythmic episodes were endogenously quenched when the rats prepared to lever-press; this inhibition of rhythmic episodes lasted through fluid delivery and consumption, making it clear that GC rhythms are not related to gustatory processing itself. By showing a direct relationship between the 7 to 12 Hz rhythm and disengagement from a task, these data provide strong and novel evidence that this gustatory rhythm in rats is associated with withdrawal from experimental contingencies.

INTRODUCTION

Physiological recordings that emphasize organized activity occurring across relatively large neural populations frequently reveal oscillatory brain events with a range of peak frequencies and foci (Buzsaki and Draguhn 2004; Destexhe and Sejnowski 2001; Freeman 2000; Niedermeyer 1993; Steriade 2000), most obvious among them a neocortical rhythm focused around 7–12 Hz. Although similar in frequency range, this oscillatory pattern is distinct from the olfactory and hippocampal θ rhythm; instead, it is similar to the human μ/α rhythms, which are characterized by high-voltage 7 to 12 Hz oscillations synchronous across neocortical space, associated with quiet immobilization, and interrupted by somatomotor activation (Arroyo et al. 1993; Gastaut 1952; Nikouline et al. 2000; Semba et al. 1980; Tiibonen et al. 1989).

Although such rhythms are ubiquitous across mammalian species and behavioral preparations, their function is hotly debated; various researchers have suggested that they may reflect either a physiological (Pfurtscheller et al. 1997; Tiibonen et al. 1989) or pathological (Buzsaki et al. 1990; Johanson et al. 2003; Robinson and Gilmore 1980; Shaw 2004; Vergnes et al. 1987) disengagement from environmental contingencies—“idling” and “absence seizure” activity, respectively (the latter being supported by the characteristic spike-and-wave shape of this oscillation). Other data, however, have led some researchers to suggest that the somatosensory μ rhythm might represent a task-oriented state (Fanselow and Nicolelis 1999; Nikouline et al. 2000), much as olfactory cortex and bulb rhythms seem related to stimulus acquisition (Bressler 1987).

It has been difficult to provide an unimpeachable argument for or against a relationship between rodent 7 to 12 Hz neocortical rhythms and perception, in part because both main hypotheses claim primary support in interpretation of a single behavioral observation—the fact that rhythmic episodes tend to happen when the animal is immobile, only to fade just before the animal moves. Specifically, the disengagement hypothesis postulates that postactivity movement rouses the animal out of the oscillatory state, whereas the anticipation/processing hypothesis postulates that the rhythms specifically predict movement. Furthermore, somatosensory cortex may not be the ideal location in which to seek a functional role for such rhythms because rats often do not rhythmically sample somatosensory stimuli in task contexts, even in the case of whisker stimuli (see Krupa et al. 2004). It might be more reasonable to examine potential relationships between neural rhythms and perception in a chemosensory system, in which stimuli are manipulated according to the 7 to 12 Hz rhythm of either sniffing or licking.

Here, we present a task in which a restrained rat’s task-oriented anticipation of stimuli can be cleanly distinguished from disengaged (idling/seizure) behavior, and show that 7 to 12 Hz rhythms have to do with the latter behavior. Furthermore, we show this effect using fluid taste stimuli, which are processed by rhythmic stimulus manipulation (licking). Local field potentials (LFPs) were recorded in gustatory cortex (GC) as rats were trained to perform a simple timed fluid self-administration similar to previously described timing/delayed-reinforcement tasks (Church et al. 1994). In these sessions, rats went through periods in which they displayed goal-oriented efforts to obtain fluid reward, and periods in which they continued to drink but put forth no organized effort to obtain the fluid. The 7 to 12 Hz rhythm, which by several criteria were identical to human and rodent μ, appeared almost exclusively...
during the period of task disengagement, and was clearly dissociable from physical and gustatory processing of liquid stimuli.

These results are the first description of oscillatory activity in the gustatory system, and the first to specifically show that the oscillatory state is related to disengagement from task orientation, rather than to anticipation of chemosensory stimuli; furthermore they provide evidence that, at least in GC, μ rhythm is not related to sensory input. We suggest that the "withdrawing" is consistent with nonpathological states (i.e., not full-blown epileptic seizure) studied in normal human subjects.

METHODS

Subjects

Four female Long Evans rats (250–300 g at the time of surgery) served as the subjects in this study. Animals were maintained on a 12-h light/12 h-dark schedule, with experiments carried out in the light portion of the cycle. Unless otherwise specified, animals in home cages had unrestricted access to chow and water.

Surgery

Animals were anesthetized using an intraperitoneal injection of a ketamine, xylazine, and acepromazine cocktail (100, 5, and 1 mg/kg, respectively). Small (20% of induction dose) injections of ketamine were delivered whenever breathing rate and hindpaw pinch response suggested that anesthesia level was becoming light. The anesthetized rat was placed on a standard stereotaxic frame, after which the scalp was slit and reflected. Holes were bored in the skull for four to six microwires. The electrodes were buried in a taste-responsive part of dysgranular insular cortex (Katz et al. 2001a, 2002).

After electrode implantation, the rat was removed from the stereotax, and intraoral cannulae (IOC) were inserted bilaterally. Thin polyethylene tubes were passed from the space between the first maxillary molar and the lip, through the masseter muscle and inside the zygomatic arch, and out through the opening in the scalp, where they were cemented to the dental acrylic cap (Phillips and Norgren 1970). The scalp was then sutured or stapled around the implant, and antibiotic ointment was applied liberally to the wound. The rat received a subcutaneous injection of penicillin (0.1 ml) immediately after surgery, and again 48 h later.

Training

Rats underwent adaptation to handling starting 2 days postsurgery, wherein the experimenter cleaned the IOCs and turned the 0–80 μm microdrive screw ¼ turn (lowering the electrodes about 81 μm); soon the electrodes were buried in a taste-responsive part of dysgranular insular cortex (Katz et al. 2001a, 2002).

Seven days after surgery, rats were begun on a regimen of mild water restriction: 30 min of water ad lib in the late afternoon. After 3 days of water restriction, they were introduced to the experimental restraint chamber, a Plexiglas box (Bermejo et al. 1998; Katz et al. 2001a; Welch et al. 1995) placed in a sound-attenuating chamber that is itself inside an isolation room. The backs of the rats’ head caps were cemented to the dental acrylic cap (Phillips and Norgren 1970). The scalp was then sutured or stapled around the implant, and antibiotic ointment was applied liberally to the wound. The rat received a subcutaneous injection of penicillin (0.1 ml) immediately after surgery, and again 48 h later.

Electrophysiology

Recordings from all microwires were initially amplified and filtered, and fed into a parallel processor capable of simultaneously digitizing 32 signals at 40 kHz (Plexon, Dallas, TX). Sixteen of these signals were split off to a separate amplifier with filtering set for LFPS recording (band-pass 3–90 Hz), and from there to a computer, where they were digitized at 1,000 Hz. LFPS, unit, behavioral, and video records were synchronized to a single clock.

Behavioral analysis

Lever presses were recorded throughout the session, which were divided in trials. Trials ended (and new trials began) with a rewarded lever press. Parameters extracted from each trial included: $j)$ total number of lever presses; $2)$ number of presses in the 10 s preceding a rewarded press; $3)$ latency of the rewarded lever press, measured from the start of the trial; and $4)$ SD of all lever press latencies across a series of 5 consecutive trials. This last variable estimates how well clustered in time the responses tend to be in a manner that is relatively insensitive to occasional early presses; the closer the rat comes to pressing only at the time of available reward, the lower this number could then be adjusted to minimize the animals’ discomfort. The rats’ front paws were unrestrained. A mirror under the floor of the chamber, placed at a 45° angle to the horizontal, allowed a small low-light video camera an unobstructed view of the orofacial region of the rat; digital video recordings were made of training sessions for later analysis of occurrence of consummatory behaviors (licking and chewing).

In the first session of restraint, lever training began. A lever was placed directly under the right forepaw, and pressing of this lever caused a 40-μl aliquot of water to be delivered (under nitrogen pressure) through the IOC into the mouth, where it was consumed (a process that involves visible licking and chewing by the rat). Rats quickly became eager to press for water. Rats were free to press at will, but over the next several sessions they were trained that they would receive water reward only after 30 s (the “foreperiod”) had elapsed since the previous delivery: lever presses made before the end of a foreperiod were unrewarded, and the first press after the end of a foreperiod (at any latency >30 s) was rewarded and restarted the clock. Figure 1 describes this training process graphically.

![FIG. 1. Timed fluid self-delivery task. This schematic displays 2 consecutive trials of the lever-press task, as if made by a rat in the task-oriented phase (see text). Bottom row of dots is the first trial, and the top row of dots is the second trial; time is on the x-axis. The rat is free to press the lever at any time, but for the first 30 s of the trial lever presses do not result in water delivery (unrewarded lever presses depicted as gray dots); under these conditions the rat quickly learns to withhold from lever pressing for approximately the first half of the period, similar to other timing tasks (e.g., Church et al. 1994). The first lever press made after the end of this 30-s interval (this response is noted with a black dot) causes a 40-μl aliquot of water to be delivered directly into the rat’s mouth and resets the clock, starting the next trial. Thus lever presses made during the task-oriented phase typically cluster in the last half of each trial (and therefore the SD of their times of occurrence is relatively low), and the rewarded press typically occurs a few seconds after the 30-s foreperiod has elapsed. Region to the right of each rewarded lever press is therefore meaningless.](http://jn.physiology.org/doi/10.2210/jn.2005.06.02.2833)
will be. For ease of visualization and to reduce the impact of single-trial outliers on the statistics, values of each parameter (except for SD) were smoothed using a sliding window of 5 trials and an overlap of 4 trials. Combinations of these parameters were used to describe each trial (see RESULTS) in an abstract 3-dimensional (3D) space, and a k-means cluster analysis method was used to divide them in two groups (Jain and Dubes 1988). This clustering method allowed the whole session to be divided in the two periods (task oriented and disengaged) as described in detail in the RESULTS, with a resolution of 5 trials, determined by the smoothing filter.

A video coder, blind to the purpose of the experiment and the behavioral state of individual rats, examined the sessions, noting periods in which the rats engaged in intensive licking/chewing behavior. The times of these bouts, as noted from the time stamps on the video record, mostly corresponded to the times of stimulus delivery. The coder noted start and end times of bouts, and calculated average bout length from these data.

Electrophysiological analysis

The marked difference in amplitude and frequency between periods of oscillatory and nonoscillatory activity allowed rhythmic episodes to be detected using a threshold-crossing method, but this method was validated by consideration of power spectral densities (see RESULTS). LFPs were first band-passed filtered, using a fast Fourier transformation (FFT) algorithm, between 7 and 12 Hz and then 7 to 12 Hz episodes were identified if the power crossed a determined threshold. Single high-voltage events were detected using a threshold-crossing method: sets of cycles separated by <1,000 ms were grouped together and considered a single episode; in this way the beginning of an episode was defined as the first high-voltage spike after a period of ≥1 s of no high-voltage 7 to 12 Hz activity, and the end of the episode was determined by the last spike before a 1-s period of low-voltage activity. We revalidated our detection method by visual inspection and by comparing the field potentials threshold-crossing method with a spectrogram threshold crossing. Once rhythmic episodes were detected, their total duration per trial was measured for both the task-oriented and disengagement periods.

Power spectral density was computed using the Welch method (Welch 1967) during periods of 7 to 12 Hz oscillations and desynchronization. Cross-correlations were estimated on unfiltered data and by computing the cross-covariance between field potentials recorded in different hemispheres during the occurrence of 7 to 12 Hz episodes and during periods of visually identified high-frequency, low-amplitude activity. To validate the correlation results obtained with the cross-covariance analysis, spectral coherence in the 7 to 12 Hz range was computed on the same data using a 0.512-s Hanning window with an overlap of 0.256 s.

To track the normalized time course of the oscillatory pattern in relation to lever presses, we directly computed the time course of the 7 to 12 Hz power in the overall spectrum during the interval surrounding each lever press (from 2 s before until 5 s after) using a sliding spectrogram window of 1.024-s duration (i.e., 1,024 points). Results were averaged to produce a smooth (also normalized) record of the impact of lever presses on 7 to 12 Hz components of the overall LFPs.

Histology

After the experimental sessions, subjects were deeply anesthetized with ketamine (150 mg/kg) and perfused through the heart with saline followed by 5% formalin in saline. Seven seconds of DC current (7 μA) were passed through selected microwires in preparation for staining. The brains were removed and immersed in a sucrose formalin mixture, where they remained, refrigerated, until fixed. Sections (80 μm) cut through the implanted areas were stained with Prussian blue for ferrous deposits blasted off the electrode tips, and counterstained with cresyl violet for cell bodies.

RESULTS

Behavior of the rat during the lever-pressing session

Four implanted, water-restricted rats were habituated to head restraint, with their head cap bolted to the front panel of the box, and were trained to use their right forepaws to press a lever for reward (usually water) at fixed intervals. Each session began with the rat positioned in front of a lever and was terminated when the rat had been in a disengaged state (see following text) for at least about 30 min. Because rats’ ability to maintain focus varied from day to day, session length varied within and between rats; the average duration of each session was 118.32 ± 24.65 min (mean ± SD), or 202 ± 43.3 trials, n = 19.

Experimental sessions could consistently be divided into two phases, reflecting a switch between behavioral states (Fig. 2). One phase (which we refer to as the task-oriented phase) was typified by organized lever-pressing activity: rats waited quietly through the initial portion of each trial, and then initiated an intense pressing regime as the end of the foreperiod approached (these lever presses are represented by the blue dots in Fig. 2A). This intense lever pressing ultimately resulted in the rat receiving fluid reward for the press just after the end of the foreperiod, at which time the trial ended and the behavioral cycle repeated. Task-oriented behavior, which lasted in this case for the first 7/10 of the session shown in Fig. 2A, resembles that observed in other simple inhibition/timing tasks (Church et al. 1994). During this task-oriented phase, each rat’s behavior was very clearly oriented toward the goal of water acquisition, in that lever pressing increased as the end of the foreperiod (and, thus the time of available fluid reward) approached.

Subjects did not maintain task-orientation endlessly, however, as the top 3/10 of Fig. 2A reveals: at a certain point the rat’s behavior undergoes a visible change, with lever presses—represented with red dots in Fig. 2A—no longer clustering near the end of the foreperiod, often occurring much earlier or later. Lever presses in this phase were still present, but were spread almost randomly throughout the trial. The rats in this phase appear to be disengaged from the task of seeking fluid at the end of the foreperiod. Thus we refer to this as the disengaged phase, suggesting only that the rat became at this point disinterested in the experimenter-devised task, and making no specific assertion concerning what internal factors (satiation, frustration, engagement in some other aspect of the environment) underlie the change (but see DISCUSSION).

Several behavioral measures related to the lever-press regimes distinguished the task-oriented from the disengaged phase, as shown in Fig. 2, B1–B3. In each, the red section of the graph represents the disengaged phase. Note that the latency at which the rewarded lever press occurred (Fig. 2B1) was consistently stable during the task-oriented phase, as was the SD of all (unrewarded and rewarded) lever-press latencies (this measure differed from the latency of reward measure in that it broadly reflected the tendency for even the unrewarded lever presses to cluster toward the end of the foreperiod; Fig. 2B2); the number of lever presses in the last 10 s preceding a reward (Fig. 2B3), meanwhile, was reliably >1 during the task-oriented phase. This pattern was consistent across sessions and animals, lasting on average 75.67 ± 20.33 min, or 114.89 ± 39.64 trials, n = 19. In contrast, rewarded lever
presses often occurred with longer latency during the disengaged phase than during task orientation (46.17 ± 10.19 s vs. 31.37 ± 0.73 s, n = 19; top 3/10 of Fig. 2B1), and the SD of lever-press times in the disengaged phase was high (16.86 ± 8.16 vs. 5.80 ± 1.02 during task oriented periods, n = 19; top 3/10 of Fig. 2B2). Also, fewer lever presses occurred in the 10 s before the reward during the disengaged phase than during the task-oriented period (0.71 ± 0.55 vs. 12.03 ± 5.25, n = 19; top 3/10 of Fig. 2B3). The projection of trials onto 3D combinations of these parameters consistently revealed a clean dissociation between periods of task-orientation and disengagement (Fig. 2C); this dissociation was further validated by k-means cluster analysis, which divided the trials into two groups (blue vs. red trials in Fig. 2C). Although we cannot say for sure that either task-oriented or disengaged trials represent single, unified clusters, the dissociation of task-oriented from disengaged trials is clearly demonstrated in this analysis.

Because shifts of rat behavior from task-oriented to disengaged typically happened with similar suddenness, it was usually possible to estimate the change point with fair accuracy. The 5-trial smoothing algorithm used in data preparation introduced a slight lack of precision in the cluster solution, but this was considered acceptable because: 1) the shift in state itself probably did not occur instantaneously, and thus there was little point in attempting to estimate it with zero error; and 2) the slight lack of precision did not impede the subsequent analysis, or the conclusions based on our suggestion that rats progressed from an obviously task-oriented mode to a disengaged mode.

7 to 12 Hz oscillations in GC

LFPs recorded in the GC simultaneously with performance of the fixed-interval reinforcement task showed periods of high-frequency, low-amplitude activity (Fig. 3, A and B1), occasionally interrupted by bursts of spike-and-wave high-amplitude activity (Fig. 3, A and B2). During these episodes, both the amplitude and the frequency content of the LFPs were distinctive; the smaller-amplitude signal was relatively flat between 7 and 12 Hz, but the high-amplitude signal included a distinctive peak of power in the 7 to 12 Hz range (Fig. 4A). Such episodes had variable duration, with an average length of 1.64 ± 1.09 s, n = 18; the calculated duration was to some degree dependent on search algorithm parameterization. Both in form and in frequency, these episodes clearly resemble classically described human and rodent \( \mu \) rhythm. For this reason, and because the resemblance extends to similarity of interhemispheric coherence and similarity of relationship to sensory and motor events (see following text), we provisionally refer to the observed rhythm as “GC \( \mu \)”.

Figure 3 also shows the action potentials of two gustatory cortex neurons during low-amplitude activity (Fig. 3B1) and GC \( \mu \) (Fig. 3B2). Although single-neuron activity was relatively stochastic during low-amplitude LFPs, during GC \( \mu \) episodes the firing was rhythmic, more synchronous, and correlated with LFPs. GC \( \mu \) is clearly intrinsic to GC.

The observed oscillatory pattern demonstrated a high degree of intra- and interhemispheric synchrony: Figure 4B shows the cross-correlograms between bilateral local field potentials recorded during periods of rhythmic and low-amplitude activity. Across sessions and animals, the average cross-correlogram peak is 0.76 ± 0.12, n = 19 for high-amplitude events recorded bilaterally, and the shape of the cross-correlogram shows ripples characteristic of coherent oscillations of nearly 10 Hz. Cross-correlograms made during periods of low-amplitude activity showed a significantly smaller peak (0.35 ± 0.08, n = 19) and no ripples of nearly 10 Hz. The difference between the central peak heights was highly significant \( r(18) = 10.6353, P < 0.00001 \). Correlation results obtained from the cross-covariance analysis were confirmed by estimating the mean coherence between signals in the 7 to 12 Hz band (Fig. 4C); the mean coherence value was 0.84 ± 0.08, n = 19 during periods of GC \( \mu \), significantly different from the one obtained during period of low-amplitude activity (0.17 ± 0.06, \( P < 0.00001 \)).
Correlation between GC $\mu$ and behavior within sessions

On the basis of the above data, we investigated the functional implications of GC $\mu$ activity by relating the occurrence of oscillatory episodes to time within a session. Figure 5A shows a session-long trace of LFPs recorded from a single GC electrode (about 2 h); the incidence of high-amplitude rhythmic activity is much higher during the last half of this session than that during the first half. When estimated times of GC $\mu$ episodes occurrence were overlaid on the trial structure, as shown in Fig. 5B (a representative session similar to that presented in Fig. 2A), a striking finding concerning the relationship between GC $\mu$ and task performance emerged. Red lines denoting the occurrence of GC $\mu$ events clearly appear only after the transition between the task-oriented and disengaged phases (k-means clustering) estimated by the horizontal arrow; black dots show unrewarded lever presses, leading to the rewarded lever presses in green. Inspection of this plot reveals that the occurrence of oscillations was largely restricted to periods of disengagement.

An analysis of all sessions in all rats (Fig. 5C) confirms this robust effect: GC $\mu$ was more prominent during the disengagement period by more than a factor of 12: rats engaged in these oscillatory episodes for about $16 \pm 8\%$, $n = 19$ of the time during disengaged trials, compared with nearly $1 \pm 1\%$, $n = 19$ during task-oriented trials [$t(18) = 8.8688$, $P < 0.00001$]. The precise trial-to-trial relationship between GC $\mu$ and behavior during the disengaged phase was modest—in trials 150–160 in Fig. 5B, for instance, the most obvious disengagement (late responses, few responses) was accompanied by relatively little GC $\mu$, whereas the intensely rhythmic activity in trials 120–130 accompanied only mildly disengaged behavior—but the more general relationship was hugely robust. GC $\mu$ seems not to directly delay responding, but rather to signal the fact that the rats are no longer engaged in the task.

This analysis makes it clear that GC $\mu$ can be dissociated from the desire to acquire fluid stimuli, but leaves unexamined the possibility that it might be related to lever pressing or stimulus processing during the disengaged phase. We investigated these issues by examining the prevalence of GC $\mu$ around the time of task-oriented and disengaged lever presses. Lever presses made during the task-oriented phase were not typically preceded by substantial incidence of GC $\mu$—as already explained, little oscillatory activity was produced during proper performance of the task. During the disengaged phase, however, prepress LFPs contained a great deal of power in the 7 to 12 Hz range (Fig. 6A). The relatively high amplitude of GC $\mu$ vanished just before the lever presses themselves. Thus

![FIG. 3. Local field potentials in gustatory cortex of awake rats show episodes of 7 to 12 Hz activity. A: representative recording of a gustatory cortex LFPs, showing bursts of high- and low-amplitude activity. B1: magnification of a period of low-amplitude activity marked with a gray horizontal line in Fig. 3A, revealing a desynchronized LFPs. Below the LFPs is the spiking of 2 concurrently recorded single neurons in GC; note the lack of obvious relationship between the single-unit firing and field potential. B2: magnification of a period of high-amplitude activity marked with a black horizontal line in Fig. 3A, revealing spike-and-wave activity. Below the LFPs is the spiking activity of the same 2 single neurons in GC, showing extensive synchronization to the rhythmic LFPs.](https://example.com/fig3)

![FIG. 4. Features of synchronized and unsynchronized activity. A: representative power spectral density plots taken from low-amplitude (dashed) and high-amplitude (solid) periods of GC LFPs. Only the latter power spectrum shows a peak at 7–12 Hz. B: representative interhemispheric cross-covariances from low-amplitude (dashed) and high-amplitude (solid) periods of GC LFPs. Note the peak at 7–12 Hz and the high level of interhemispheric correlation during periods of spike-and-wave activity. C: histogram showing the mean coherence value in the 7 to 12 Hz range across sessions and animals. Black: coherence during GC $\mu$ episodes; gray: coherence during low-voltage activity.](https://example.com/fig4)
in the disengaged phase GC did not predict acquisition of fluid, but rather was inhibited by movement, just as previously reported in studies of similar somatosensory rhythms (Pfurtscheller et al. 1997). Figure 6 also reveals robust evidence that this pattern in GC is in no way involved with gustatory (taste) processing. 7 to 12 Hz power recovers after lever press, but that recovery is much slower when the lever press is rewarded by fluid delivery. In the disengaged phase, power in the 7 to 12 Hz range recovers to about 50% of its original peak in the 2nd second after an unrewarded lever press (Fig. 6A). In contrast, after a rewarded lever press (i.e., one that results in fluid delivery) it recovers to only 15% of its peak power in that time (Fig. 6B), and only reaches nearly 50% in the 4th second after delivery. Subsequent video analysis of a subset of sessions for each animal, done by an observer blind to the purposes of the study, revealed that consumption of the administered liquid, as measured by licking/chewing, was very similar to the length of the pause in oscillations after rewarding lever press: licking/chewing bouts after liquid delivery averaged 2.59 ± 0.88 s, n = 9 during the disengaged phase. It can be assumed that swallowing occurred during (and before the conclusion of) these licking/chewing bouts. Stimulus processing and rhythmic mouth movements, both of which follow close on the heels of stimulus delivery, inhibit GC; thus it is unlikely that either of the two is the major determinant of the neural oscillations.

As one final test of this hypothesis, 3 rats received one session in which sucrose, a highly effective tastant, replaced water as the fluid reward. In these sessions, disengagement occurred as suddenly as during water sessions, and again GC appeared almost exclusively during the disengaged phase (Fig. 7A). Also as in water sessions, impending lever presses quenched GC, and again this inhibition lasted for the 5 s of processing/consumption of administered fluid (Fig. 7B). Thus GC clearly has nothing to do with taste processing in this task, regardless of whether the taste is water or sucrose.

DISCUSSION

The important results of this investigation can be summarized as follows: 1) head-restrained rats’ performance on a long-delay fluid self-administration task can be characterized in terms of distinctive task-oriented and task-disengaged phases; 2) high-amplitude, bilaterally coherent 7 to 12 Hz oscillations occur in gustatory cortex during the latter, but not the former phase; 3) all properties of these oscillations—shape, frequency, spatial extent, and their relationship to stimulus presentation and movement initiation—resemble those of rhythms frequently observed in rodent and human somatosensory cortex; and 4) gustatory processing does not itself engender GC, as shown by the fact that inhibition of this rhythm by water or tastant delivery lasts through processing/consumption of the fluid. Thus we conclude that GC occurs in
includes information lever press, because the 1-s sliding window used to produce the spectrogram slower. 12 Hz power recovers over the next 1–3 s; after the latter, recovery is much bottom.

Unrewarded (top) and rewarded (bottom) lever presses. Time of lever press is noted by the black dot. Note that the inhibition of GC μ lasts much longer after fluid delivery. B: across-subjects averages showing that normalized power in the 7 to 12 Hz range (y-axis) decreases dramatically just before unrewarded (top) and rewarded (bottom) lever presses. After the former, 7 to 12 Hz power recovers over the next 1–3 s; after the latter, recovery is much slower. x-axis of this plot ends at 4 s post lever press rather than at 5 s post lever press, because the 1-s sliding window used to produce the spectrogram includes information ≈5 s after lever press in the 4-s data point.

gustatory cortex of the active rat, where it appears to be related to a state of disconnection from external stimuli and contingencies.

Oscillatory activity in gustatory cortex

Local field potentials recorded in the gustatory cortex reveal alternating periods of low-amplitude, high-frequency activity with periods of high-voltage oscillations. High-voltage events are characterized by a spike-and-wave shape, with a sharp negative deflection followed by a positive slow wave, and have a frequency of 7–12 Hz and a high degree of interhemispheric synchrony. All of these properties are in agreement with previous reports of the 7 to 12 Hz rhythm in other cortical areas of rodents (Buzsaki et al. 1990; Shaw 2004; Wiest and Nicolelis 2003) and humans (Arroyo et al. 1993; Nikouline et al. 2000; Tiihonen et al. 1989).

Gustatory cortex is adjacent to somatosensory cortex; this raises the theoretical possibility that the rhythm recorded in GC could actually be observed as an effect of volume transmission. The correlation between single-unit activity and local field potentials at single electrodes, however, supports the conclusion that the observed activity was local in nature. It is possible that GC oscillations could be synchronous with those generated in the somatosensory thalamocortical axis; this possibility will be addressed in future studies.

Oscillations and non-task-oriented behavior

7 to 12 Hz oscillations in rodents are associated with awake immobility and extinguished by sensory stimuli or movement (Buzsaki et al. 1990; Hartmann and Bower 1998; Nicolelis et al. 1995). This one basic result has been interpreted by some as demonstrating that 7 to 12 Hz oscillations reflect a state of “idling” and by others as evidence that they represent preparation to process incoming sensory stimuli. The behavioral test used in this report, a fixed-time fluid self-administration task, allows us to unambiguously dissociate the two behavioral states possibly associated with GC μ. Rats involved in this task were either engaged, with intense lever pressing preceding the end of the foreperiod and fluid reward collected shortly after, or disengaged from the task, with fewer lever presses often occurring long after the end of the foreperiod. In either case, the rats spent much time immobile, and in both cases the immobility preceded movement and stimulus acquisition, but only in the disengaged phase was the immobility associated with GC μ.

Rats’ behavior in the late phase could hypothetically reflect any or all of several internal factors, including most obviously lack of thirst (others include frustration and fatigue), but several observations lead us to doubt that satiation alone provides a complete and compelling explanation of disengagement. First of all, the amount of water delivered across the task-oriented portion of the session, typically in the order of 8 ml (40 μl × 202 trials), is far less than that required to satiate a water-restricted rat. In fact, the rats continued to consume fluid deliveries during the last phase—something that they would not have done if completely satiated. They also routinely consumed about 5 ml of water in their home cages after the session. For this reason, we simply refer to the last phase of the session as the disengaged phase.

Relationship with licking and chewing

The absence of the GC μ during chewing/licking in response to intraoral delivery of fluids excludes an implication of this rhythm in gustatory processing. If the function of this rhythm were related to licking, one would expect to observe this oscillation during periods after fluid administration, similar to the way that olfactory θ occurs in tight correlation to sniffing.

FIG. 6. Lever pressing and fluid consumption interrupt ongoing GC μ. A: representative LFPs traces demonstrating that quenching of GC μ accompanies both unrewarded (top) and rewarded (bottom) lever presses. Time of lever press is noted by the black dot. Note that the inhibition of GC μ lasts much longer after fluid delivery. B: across-subjects averages showing that normalized power in the 7 to 12 Hz range (y-axis) decreases dramatically just before unrewarded (top) and rewarded (bottom) lever presses. After the former, 7 to 12 Hz power recovers over the next 1–3 s; after the latter, recovery is much slower. x-axis of this plot ends at 4 s post lever press rather than at 5 s post lever press, because the 1-s sliding window used to produce the spectrogram includes information ≈5 s after lever press in the 4-s data point.

FIG. 7. Sucrose self-administration quenches GC μ. A: similar to Fig. 5C; the percentage of each trial (y-axis) spent in a GC μ during the task-oriented (left) and disengaged (right) periods; a 13-fold difference separates the two periods. B: similar to Fig. 6A, a representative trace demonstrating that a lever press leading to sucrose delivery (small circle under trace) inhibited GC μ, and that this inhibition lasted approximately 3 s—a length of time spanning gustatory processing (Katz et al. 2001a) and consumption (according to video records).
Although high-amplitude neural rhythms in the olfactory system seem intrinsically related to sensory inputs (see, for instance, Fontanini et al. 2003; Haberly 1997; Kay et al. 1996), the occurrence of the GC μ is simply not related to the physical or chemosensory processing of tastants.

Orofacial rhythms are not without neural correlates in gustatory cortex, however: oscillations related to tongue/mouth movements are reflected in the activity of single units in gustatory cortex of awake, tasting rats (Katz et al. 2001a). Such activity has little impact on the LFPs, probably because it comes from only a small subsample of GC neurons. As a group, GC neurons show little resonance in the 7 to 12 Hz range (see Fig. 7A of Katz et al. 2001a) during performance of a tasting task, further suggesting that the observed rhythms are unrelated to licking.

Functional interpretation

What then is the function, if any, performed by the GC μ? By using a task in which a clear behavioral dissociation can be observed as rats first apply themselves to, and then withdraw from, a timed lever-press task, we are able to provide a preparation in which the two theories make testably distinct predictions, and our results are robust: in our hands GC μ reflects a coherent, bilateral cortical state related to disengagement from task orientation.

Although it is difficult to dissociate “idling” from epilepsy, several facts argue against the strong conclusion that our rats were experiencing full-blown seizures. First, late lever presses were frequently preceded by trials with little rhythmic activity, rather than letting fluid drip out of their mouths; this result, analogous to earlier work in somatosensory cortex (Wiest and Nicolelis 2003), distinguishes the behavior of normal rats amid a GC μ episode from that typically observed during epileptic seizures (Cooper and Upton 1978; Snead 1995). Most tellingly, the relationship between GC μ and behavior observed here is precisely that observed in research on normal, nonepileptic humans, who demonstrate poor task orientation during episodes of 7 to 12 Hz somatosensory (Slobounov et al. 2000) or visual (Molle et al. 2002) rhythms; this contrasts with the successful task performance that accompanies cortical and hippocampal θ rhythms (Sederberg et al. 2003; Semb and Komisaruk 1984). The occurrence of 7 to 12 Hz rhythms is related to loss of focus or attention, but is not necessarily pathological.

Nonetheless, we would suggest that the hard demarcation of a boundary between such mammalian rhythms and seizures is uncalled for. It may be possible to conceptualize absence seizure as a condition of “poorly controlled” normal rhythmicity. Full-blown absence seizures might therefore be described as extreme cases of disengagement, abnormal in duration and in its relationship with contingencies, and thus to be consistent with the rhythms observed here.

In conclusion, by bilaterally recording gustatory cortical activity in both hemispheres while simultaneously observing easily defined patterns of fluid task-related (and unrelated) behavior in rats, our data provide novel insight into the nature of rhythmic activity in the brain. We have demonstrated the ubiquity of rhythmic phenomena in the 7 to 12 Hz range, and have extended our understanding of their function in a manner consistent with the extant literature. It appears that 7 to 12 Hz rhythms consistently arise—during sleep (i.e., spindles) (Kandel and Buzsaki 1997; Steriade and Contreras 1998), quiet resting (Nicolesis et al. 1995), or absence seizures (Snead 1995)—when, for one reason or another, the animal is subject to relatively low intensities of sensory input. We argue that the 7 to 12 Hz oscillation might therefore reflect the intrinsic dynamics of cortical loops, a systemwide process involving the emergence of large populations of neurons into a dynamic state (Fanselow and Nicolesis 1999; Hartmann and Bower 1998). Sensory activation results in the inhibition of the 7 to 12 Hz rhythm, temporarily promoting a shift of the thalamocortical system toward a more stimulus oriented, activated state.

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References


