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Chapter 16

Why Do We Yawn? Past and Current Hypotheses

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Abstract

Yawning can be regarded as a prototype of stereotypical behaviors that has been recycled through evolution for different purposes. These purposes are combined with the increasing complexity of the central nervous system during evolution, and correlated with the richness of social interactions. In this chapter, past and current hypotheses concerning the generation and usefulness of yawning are discussed.

Introduction

Cognition, emotion, behavior and memory are all brain functions. However, this was not accepted to be true until the end of the 18th century. While eating, drinking, urination, sight and walking seem easy to understand, the purposes of other functions that originate in the brain, such as sleep, dreaming, hiccups and laughter, remain mysterious. Yawning belongs to this second group of functions, which appear more difficult to understand than the other functions of the brain. This might explain the vast array of beliefs and hypotheses, as varied as they are strange in certain cases, associated with what, for a human being, is a daily behavior. As we shall see, several diverse hypotheses exist in 2011, but for the moment none can be scientifically verified.

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What Is a Yawn?

Yawning is a stereotyped, and often repetitive, motor action characterised by gaping of the mouth accompanied by a long inspiration of breath, a brief acme, and then a short expiration of breath. Stretching and yawning simultaneously is known as pandiculation, which is not merely a simple opening of the mouth but a complex, coordinated movement bringing together a flexion followed by an extension of the neck and a wide dilatation of the pharyngolarynx with strong stretching of the diaphragm and anti-gravity muscles. Yawning is involuntary and only humans seem capable of altering its occurrence for cultural or social reasons. It is highly stereotypical because no environmental input changes the sequence of movements. Yawning is observed in cold-blooded and warm-blooded vertebrates, from reptiles with rudimentary "archaic" brains to human primates, in water, air and land environments. Ethologists agree that almost all vertebrates yawn. Yawning is morphologically similar in reptiles, birds, mammals and fish (Deputte 1994; Fraser 1989; Walusinski and Deputte 2004). These behaviors may be ancestral vestiges maintained throughout evolution with little variation (phylogenetically old origins). Correlatively, yawning can be viewed as early as 12 weeks during fetal development, and is considered an ontogenetically primitive behavior (Walusinski 2010).

Different Types of Yawns

The triune brain hypothesis is a model of the evolution of the vertebrate forebrain and behavior proposed by the American neuroscientist Paul D. MacLean (1913-2007). MacLean originally formulated his model in the 1960s, and propounded it at length in his 1990 book *The Triune Brain in Evolution*. The triune brain consists of the reptilian complex (archaic brain), the paleomammalian complex (limbic system), and the neomammalian complex (neocortex), viewed as structures sequentially added to the forebrain in the course of evolution (McLean 1990). Although the model never won wide acceptance among comparative neurobiologists, it helps to explain the different types of yawns:

1. “Universal yawning”, which is seen in nearly all vertebrates, is associated with sleep and arousal or with hunger and satiety, and appears to be generated by the reptilian brain (Giganti et al. 2010; Giganti and Salzarulo 2010);
2. What ethologists describe as “emotional yawning”, which is only seen in some mammals (but data are still being collected), and is generated by the paleomammalian brain. This is the yawn that helps to pacify after stress. Dogs in veterinary situations or caged chimpanzees yawn more frequently than during non-stressful times. Ethologists call this type of behavior a displacement activity. In humans, athletes yawn repeatedly before competitions, as do parachutists before jumping, and actors before making their entrance. In these cases, yawning has a calming, anti-stress effect. This might explain why yoga teachers use yawning to relax their students. A related type of yawning is that associated with sexuality in dominant male macaques, who yawn repeatedly before mating, as if to make their status within the group known. This sort of yawn disappears following castration and

reappears if testosterone is injected (Aureli and de Waal 1997; Beckmann and Zimmer 1981; Deputte 1994; Deputte et al. 1994; Maestripieri et al. 1992; Zucker et al. 1998);

3. "Contagious yawning", which is observed only in great apes and humans who display a theory of mind. This ability to respond to yawning in others is absent in autistic people. Functional imaging shows activation of the same brain structures as those used to decode empathy. As a neocortical activity (frontal and parietal lobes, insula and amygdala), communicative yawning is a sign of involuntary empathy (Helt et al. 2010; Senju 2010). One can conclude that, through evolution, a behavior can be recycled for different purposes according to the increasing complexity of the central nervous system, correlated with the richness of social interactions.

Neuropharmacology of Yawning

Most of the significant advances towards our understanding of the neuropharmacological regulation of yawning have been made during the past 50 years. We now know that a variety of neurotransmitters and neurohormones are involved in the induction and regulation of yawning, including acetylcholine, dopamine, glutamate, serotonin, oxytocin, gamma-aminobutyric acid (GABA), opioids, adrenergics and nitric oxide, as well as the pro-opio-melanocortic-derived peptides, e.g., adrenocorticotropic and alpha-melanocyte stimulating hormones (ACTH and alpha-MSH, respectively). Most yawning is mediated by at least three distinct pathways, all of which appear to converge on cholinergic neurons within the hippocampus, despite the diverse set of neurotransmitters involved. In addition, the importance of the hypothalamus (parvocellular nucleus, PVN) in regulating yawning has been demonstrated, as many of these neurotransmitters appear to affect yawning through their interactions with oxytocinergic neurons within the PVN. For instance, activation of these oxytocinergic neurons by dopamine, glutamate, nitric oxide and oxytocin is known to induce yawning, whereas inhibition of these neurons by μ-opioids and GABA has been shown to reduce the frequency of yawning. It is important to note that although the effects of ACTH and alpha-MSH are also mediated by the hypothalamus, the induction of yawning by these peptides does not involve oxytocinergic neurons. Similarly, the induction of yawning by serotonin is known to occur independently of oxytocinergic neurons within the PVN; however, the brain regions responsible for serotonergic yawning are currently unknown.

Despite the great advances made towards our understanding of the neuropharmacological regulation of yawning, further studies are needed to elucidate fully how these neuro-transmitter systems interact with each other, as well as the specific receptor subtypes and brain regions involved in the induction and inhibition of yawning. Such an understanding would not only advance the use of yawning as a tool for the pharmacological characterization of receptor subtype-selective agonists, partial-agonists and antagonists, but also further our knowledge of how a variety of environmental and pharmacological manipulations (such as dietary conditions or chronic drug treatments) affect the receptor systems involved in mediating yawning. In addition, a more complete understanding of the neuropharmacological regulation of yawning could also provide insight into the specific roles of different neurotransmitter systems and/or receptor subtypes in the occurrence of yawning under a variety of physiological conditions and disease states in which changes in the frequency of yawning are known to occur (Collins and Eguibar 2010).

Old Theories Now Considered False

Life, in all its aspects, has always given rise to thought and questioning. Explanations of physiological phenomena have always provided us with reassurance. As noted by Henry Louis Mencken (1880-1956): "Explanations exist and have always existed, because there is always a simple solution to each human problem, a clear solution that is plausible and false" (Mencken 1934). The history of knowledge about yawning is a perfect example of this precept. The causes and consequences of this intriguing phenomenon have defied the human mind for centuries. The most ancient theory on yawning was described in *De flatibus liber,* "a treatise on wind" written by Hippocrates in 400 BC. He observed: "Yawning precedes a fever, because the large quantity of air that has accumulated ascends all at once, lifting with the action of a lever and opening the mouth; in this manner the air can exit with ease. Like the large quantities of steam that escape from cauldrons when water boils, the accumulated air in the body is violently expelled through the mouth when the body temperature rises". This idea persisted until the 17th century (de Mercy 1831).

Santori Santorio (1561–1636), or Sanctorius of Padua, was a physician in Venice and a student and friend of Galileo. He may be considered as one of the founders of experimental physiology. He tried to quantify physiological and pathological phenomena with measuring devices such as the scale, the thermometer and the metronome. With a scale of his own invention, he measured and compared weight gain and loss in humans, particularly by perspiration. He built an entire medical theory based on weight differences related to nutrition and releases via the emunctories and perspiration, calling it static medicine. He mentioned yawning in his aphorisms: "Yawning and limb extension after sleep show that the body perspires abundantly, similar to the rooster that flaps its wings before it starts to sing. The urge to yawn and stretch the limbs upon waking stems from the abundance of perspirable matter, creating an inclination to perspire. Through yawning and limb extension, we perspire more in one half hour than we would during other times in three hours" (Santori 1634).

Johannes de Gorter (1689–1762), a prolific Dutch author in all areas of medicine in the early 18th century, holds a key place in the history of the knowledge on yawning. In his book, *De Perspiratione insensibili* in 1755, he attributed yawning "to a need for faster blood circulation and to cerebral anemia" (de Gorter 1725). This marks the birth of an idea that would persist for two centuries, repeated by almost all authors: yawning improves brain oxygenation. This hypothesis seems to predict that yawning is triggered when blood or brain oxygenation is insufficient, i.e. when oxygen (O_2) levels drop and carbon dioxide (CO_2) concentration rises. Provine *et al.* demonstrated, in 1987, that healthy subjects who are exposed to gas mixtures with high levels of CO_2, or to physical exercise, do not yawn more frequently. Similarly, high levels of O_2 had no influence on the yawning rate (Provine *et al.* 1987). Although hypoxia is frequent in patients with heart or lung disease, no increased yawning is usually observed in these patients. Yawning in the human fetus and in fish also rules out this hypothesis. During periods of low blood oxygenation, yawning does not increase and thus cannot improve brain oxygenation.

Hypotheses That Have not Been Experimentally Tested

A number of other hypotheses have arisen over time. Cahill (1978) argued that yawning prevents lung atelectasis; Pellatt *et al.* (1981) suggested that the thyroid gland may be compressed during yawning, with the resultant liberation of thyroid hormones; Forrester (1988) presumed that yawning renews the surfactant film in the lungs; McKenzie (1994) thought that yawning may enhance the evacuation of the tonsilar fossae. Because yawning opens the Eustachian tubes and therefore ventilates the tympanal cavities, Laskiewicz, in 1953, proposed that yawning may be a "defence reflex" to equalise air pressures in the ear, triggered by altitude changes or other conditions leading to air trapping in the middle ear.

Matikainen *et al.* (2008) argued that yawning causes movements and compressions that may affect the carotid body, which is situated strategically at the bifurcation of the common carotid artery. Thus, yawning may stimulate the carotid body by compression. The carotid body is a chemosensory organ that monitors blood chemicals and initiates compensatory reflex adjustments to maintain homeostasis. The 'afferent' sensory discharge induced by changes in blood chemicals, e.g. low PO_2 (hypoxia), is relayed by carotid sinus nerve fibers. A parallel autonomic (parasympathetic) 'efferent' pathway that is the source of carotid body inhibition is less well known. These autonomic neurons are embedded in 'paraganglia' within the glossopharyngeal and carotid sinus nerves. While the phylogeny of the carotid arteries is well established, the phylogeny of the carotid body is not. Peripheral respiratory O_2 chemoreceptors are found in multiple, dispersed sites in fish and amphibia; this is reduced to a single dominant receptor site in birds and mammals. In the process, the cells in the fish gill associated with O_2 chemosensing have been replaced by the glomus cells of the mammalian carotid body. Despite this, all these vertebrates, with or without carotid bodies, yawn widely (Campanucci and Nurse 2007; Milsom and Burleson 2007).

None of these hypotheses explains the association of yawning with arousal and sleepiness. None of these proposals have been experimentally tested, and there is currently no evidence for such mechanisms.

Why a Fetal Yawn?

The advent of ultrasound technology in the 1970s enabled live, unobtrusive observations of fetal behaviors in humans, vastly increasing our knowledge of many types of subtle motor activity (swallowing, respiratory movements, smiling, and yawning), and thus of human fetal development. Yawning is a phylogenetically old, and thus ontologically precocious, behavior. Ultrasound investigation reveals its onset at between 11 and 15 weeks of gestation. The fact that yawning has survived without evolutionary variation suggests its importance in terms of developmental need. The strong muscular contraction involved in yawning has a metabolically expensive cost. If we agree with the terms of Darwin's evolutionary propositions, the cost in brain activity must be outweighed by the advantages gained in terms of developmental fitness. Thus, a structural hypothesis suggests an activating role in neurotrophin synthesis, leading to a cascade of new synapse formation or recruitment and activation throughout the diencephalon, brainstem and spinal cord. The phenomenon of activity-dependent development has clearly been shown to be one mechanism by which early sensory or motor experience can affect the course of neural development. Activity-dependent development may be a ubiquitous process in brain maturation by which activity in one brain region can influence development in other regions. These suggestions are difficult to prove, however, because human research on prenatal programming of behavior is intrinsically correlational, never manipulatively experimental, and frequently based upon homologies with other vertebrates (Almli *et al.* 2001; Petrikovsky *et al.* 1999; van Woerden *et al*. 2008; Walusinski 2010).

Current Theories under Scientific Discussion

In this section, we will only discuss universal vertebrate yawning, i.e. the oldest yawning in phylogenetic terms, which is generated by the reptilian brain. So far, sereval theories are currently under consideration, as follows:

The Arousal-sleepiness Hypothesis

Each individual, from his or her own experience, is aware of the link that exists between fatigue, sleepiness and yawning. Monotonous circumstances lead to yawning, such as idle waiting, public transportation and long periods of motorway driving. A correlation exists between the degree of sleepiness and increased yawning frequency. Furthermore, yawning exhibits a circadian rhythm. Following sleep, it is more frequent and associated with stretching (the term pandiculation is used, referring to yawning together with generalized stretching of anti-gravity muscles). It is also more frequent during the drowsiness that precedes sleep (Giganti *et al*. 2010). Herbivores, which sleep less and have shorter periods of paradoxical sleep than carnivores or frugivores, yawn less often. Yawning and pandiculation lead to the maximal opening of the upper respiratory tract and increased muscle tone in anti-gravity muscles.

All motor activity results in adaptive feedback. The strong muscular contraction involved in yawning and pandiculation initiates sensory feedback, via the somatosensory tract (posterior funiculus), with projection to the locus ceruleus (trigeminal-cervical-spinal sensorimotor loops), the ascending reticular activating system in the brainstem, and the lateral hypothalamus. According to the most developed theory at this time, the physiological function of yawning is to stimulate vigilance rather than arousal, together with muscle tone, through feedback to the above-mentioned structures, which play a role in arousal, vigilance and muscle tone. One of the main arguments for this arousal enhancement derives from the observation that yawns are followed by a significant increase in motor activity. Notwithstanding, sleepy individuals trying to stay awake change their body position and move their limbs. These movements have an arousing effect measurable by EEG, just as yawning has (Walusinski 2006).

According to Guggisberg *et al.* (2007) "the increased motor activity observed after yawns is probably not an indicator of an arousing effect of yawning, but an effective countermeasure against the underlying drowsiness". They analyzed spectral EEG changes after yawns in humans and the results were negative. Yawning activates the autonomic system but Guggisberg *et al*. suggested that this is non-specific and related to the associated movements and respiration. These researchers noticed no specific increase in skin conductance (indicating increased arousal level) after yawning (Guggisberg *et al.* 2007). Note that the hypothesis explored was that yawning induces arousal, whereas the initial theory was to interpret yawning as a means of stimulating vigilance, and not specifically arousal.

Pandiculation in Interoception and the Body Schema

Given the demonstration that yawning does not impact arousal, the theory that vigilance rather than arousal is stimulated can be reformulated. In the Aristotelian tradition, school children learn that we have five senses. But we receive information from a sixth sense, interoception, which includes proprioception, i.e. the ability to perceive sensory stimuli inside our bodies. The term interoception, related to somaesthesia, was proposed by Sherrington, as was the term proprioception (Sherrington 1906). Arousal is essential to consciousness, and requires the ability to integrate sensory information about the outside world as well as our sensations concerning our internal physical state, modulated by emotion and memory.

Afferent sensations from the musculoskeletal system converge, via the spinothalamic and spinoreticular tracts, on the thalamus and raphe nuclei and from there, on the thalamocortical tract to the postcentral gyrus in the parietal lobe. The thalamus and the paraventricular nucleus in the hypothalamus are part of a circuit that sends and receives signals from the locus ceruleus and the mammillary bodies; all of these structures are involved in autonomic reflexes. The cranial trigeminal (V), facial (VII) and vagus (X) nerves and the motor and/or sensory cervical nerves C1-C4 also convey somaesthetic information that converges on the nucleus of the solitary tract (NTS). The NTS is an interface for the peripheral information needed to stimulate the ascending reticular activating system in the brain stem, particularly the locus ceruleus, which activates arousal systems (adrenergic system at the pons, dopaminergic system at the peduncles, histaminergic system at the hypothalamus and cholinergic system at the nucleus basalis of Meynert). The neurons of the NTS project to the parabrachial nucleus, which in turn projects to various brain stem, diencephalic and thalamic sites. These structures also project to the visceral sensory area of the insula, amygdala and lateral frontal cortex, especially the right lateral frontal cortex. These circuits enable a subcortical homeostatic activity that is unconscious and automatic to result in a conscious representation. Autonomic, somatic and limbic integration make it possible to extract bodily perception, which may in turn lead to a sensation of pleasure (Cameron 2002; Craig 2003; Critchley *et al.* 2004). Thus, muscle tone variations in peripheral anti-gravity muscles, transmitted by these pathways, may trigger yawning and pandiculation which, through the powerful muscular contractions that accompany them, may activate vigilance systems.

Our perception of musculoskeletal activity, therefore, brings a feeling of well-being and a more acute bodily reflectivity of the self, for example during arousal, as proposed by the James-Lange theory of emotion or by Damasio's somatic marker hypothesis of consciousness (James 1884; Lange 1885; Damasio 1999).

Auto-regulation of the Locomotor System

For Bertolucci (2011), "pandiculation seems to be elicited by a complex array or sequence of stimuli, which might include both exteroceptive signals (e.g. light-darkness) and interoceptive ones (e.g. circadian endocrine cycles and somatic interoception). Yawning is a series of coordinated actions that unfold sequentially, building up soft tissue contractile tension to a peak, at which point the joints of the limbs and trunk are maximally extended or, alternatively, the trunk is arched in flexion. After the peak, the soft tissue tension level plummets, yielding a sense of pleasure and well-being. The actions can be regional or involve the whole body, and are often bilaterally symmetrical". The musculoskeletal system is constantly being reshaped by the mechanical constraints to which it is exposed. For example, prolonged immobilization leads to muscle loss and skeletal demineralisation.

Bertolucci (2011) argues that "pandiculation with its specific and vigorous muscle activity, might be a means to compensate for the mechanical signals delivered by rest periods and sub-optimal movements". Yawning might be considered a feedback mechanism resulting from stiffness, and possibly be triggered by extended periods of immobility in asymmetrical positions. If the body tends to stiffen, pandiculation "can serve to restore the limb (and related musculature) to an original (homeostatic) state".

Pandiculation "might be a biological compensation for periods of immobility and/or vicious body positions, restoring the animal's mobility by breaking up abnormal muscle metabolism cross-links formed by inactivity or suboptimal activity". "Perhaps the vigorous co-contractions of pandiculation systematically reshape the structural linkage among segments and simultaneously signal the cells (via mechanotransduction) to synthesize the cellular muscle components required to maintain the appropriate environment. If so, pandiculation might help restore optimal musculoskeletal arrangements, and thus optimize motor capabilities" (Bertolucci 2011).

The Thermoregulation Hypothesis

The existence of yawning across almost all vertebrate species suggests important basic functions, and the spontaneous and involuntary nature of a yawn lends support for it having adaptive significance. Recent research by Andrew C. Gallup (2010, 2011) suggests that one biological function of yawning among homeotherms is central thermoregulation. Comparative research from birds, rats and humans suggests, for them, that yawning reduces brain and body temperature, and is influenced by the range and direction of ambient temperature change. According to this model, the increased facial and brain circulation that follows yawning acts like a radiator, by eliminating calories from the blood in the brain via the face and head, and by introducing cooler blood from the extremities and lungs into the brain. In one of the experiments developed by this team, subjects wore refrigerated packs on their foreheads. Under these conditions, they were less susceptible to contagious yawning than with no forehead refrigeration. It should be noted that cold temperatures have an arousing effect and can, by themselves, modify the outcome. Other experiments on birds in various temperature conditions showed an increased frequency in the number of yawns with increasing temperature. However, no other parameters that could interfere with this finding were taken into consideration, which significantly limits the scientific value of this study (Gallup 2010, 2011). Until direct, intraparenchymal measurements can be performed, this theory will not be acceptable.

Furthermore, according to calculations by Hannu Elo, this hypothesis is physically impossible. It is impossible to lower body temperature through yawning, unless the yawns result in heavy perspiration. Similarly, yawning cannot lower brain temperature, which would require water evaporation (lungs and respiratory tract), loss by conduction, thermal radiation, and a slowdown in metabolism (Elo 2010, 2011). In addition, this explanation overlooks the existence of fetal yawning and yawning in poikilotherms such as reptiles. For these reasons, the hypothesis of brain cooling through yawning obviously requires further analysis, with due consideration given to anatomy and physiology as well as the actual need, if any, to cool the brain.

Yawning and the Cerebrospinal Fluid System

Domenico Cotugno was the first, in 1764, to describe the circulation of cerebrospinal fluid (CSF) (Cotugno 1988). The beating of the heart and the movements associated with breathing cause pressure variations in the ventricular system. Each deep inhalation is followed be an increase in CSF flow rate in the fourth ventricle (Schroth and Klose 1992).

Jaw kinematics, together with inhalation, have been shown to alter intracranial circulation. Lepp (1982) describes jaw kinematics as follows. Jaw movements activate the pterygoid musculovenous pump, located in the upper part of the anterior parapharyngeal space, known as the prestyloid parapharyngeal space. As a result, this pump, also known as the paratubal pump, can impact the mechanism of venous blood flow out of the endocranium, mainly via the plexus venosus foraminis ovalis. The pterygoid cistern, a component of this pump, corresponds to the cavernous part of the pterygoid plexus. It is an extracranial extension of the cavernous sinus and passes through the foramen ovale. It plays an important role as an intermediary station of acceleration for return blood flow from the brain (Bouyssou and Tricoire 1985; Patra *et al*. 1988). Lepp notes that it would be reasonable to consider jaw kinematics together with the lateral pterygoid muscle as a venous trigger, given that they act as the starter for the alternating musculovenous pumping action that takes place in the cavernous part of the pterygoid plexus. This pumping action is particularly efficient during isolated yawning, especially when the mouth reaches its maximum opening. However, Lepp emphasizes that yawning itself is often merely the initiation of a musculovenous motor chain reaction, which extends to the limbs and the entire skeletal musculature as tonic waves propagated in the rostrocaudal direction, and ends at the tips of the fingers and toes (Lepp 1982).

It would thus appear that the large inhalation and maximal opening of the mouth accelerate the circulation of CSF. Already, in 1912, Legendre and Piéron had demonstrated the presence of a hypnogenic factor in the CSF, which accumulates during the waking state (Legendre and Pieron 1912). Almost a hundred years of research into the hormonal, non-neuronal factors that induce sleep has identified over 50 molecules. Of current interest is prostaglandin PGD2, a hormone that acts locally and is produced by the meninges. When it binds to a specific receptor, transduction occurs from the leptomeninges to brain parenchyma through the activation of adenosine production, which induces sleep in the ventrolateral preoptic (VLPO) nucleus of the anterior hypothalamus (Huang *et al*. 2007, 2011). Yawning and pandiculation may accelerate clearance of PGD2, thus reducing sleepiness. They may also act on other neuromediators that are currently unknown.

Conclusion

We close this survey of the different functional theories on yawning, none of which have been scientifically demonstrated, by proposing that yawning appears to be a homeostatic process involving circadian variations in vigilance and emotion. Yawning externalizes a parasympathetic stimulation during the balancing of adrenergic and cholinergic homeostasis of the autonomic nervous system. Thus, it seems closer to a behavioral stereotypy than to a reflex. This is, indeed, a curious behavioral display, and is a beautiful example of an involuntary expression that is pleasurable and that we, as humans, use voluntarily to communicate boredom deliberately.

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