NEUROPHYSIOLOGICAL MODEL OF ALTERED STATES OF CONSCIOUSNESS INDUCED BY BREATHING TECHNIQUES

Zaccaro A.[1] and Penazzi G.[2]

ABSTRACT: This paper is based on recent research on animal and human models related to the physiology of respiration. It aims at building an initial neurophysiological model of breathing practices, in order to explain how these techniques induce altered states of consciousness in humans. Confirming traditional long-term knowledge from the East, we suggest that air-induced mechanical nasal stimulation is crucial for reaching meditative states of consciousness during breathing practices. In a time of rapidly emerging data about higher-order functions of respiration, we speculate that the fine-tuned modulation driven by breathing on the interaction between brain and peripheric systems is possible only if it is associated with rhythmic oscillations from the olfactory bulb, dependent on nasal mechanical stimulation. We therefore consider the complex interactions between the modulation of the respiratory frequency, the training of voluntary top-down focused attention, and the specific breathing route involved, as a critical triad associated to meditative states of consciousness induced by breathing techniques. Further studies should investigate this hypothesis and the functional correlates involved in breathing techniques, adopting EEG and fMRI techniques, as well as new methods for phenomenological analysis of subjective experience.

KEYWORDS: Breathing techniques; Pranayama; Slow breathing; Nasal breathing; Olfactory epithelium; Consciousness; States of consciousness; Psychophysiology; Neurophysiology

INTRODUCTION

Since ancient times, in eastern and western culture, breathing has been considered one of the most important tools to reach inner states of peace, contemplation, and meditation (Patanjali, Yoga Sutras). In the East, breathing techniques that aim at regulating respiratory parameters (frequency, deepness etc.) are called Pranayama (literally, "the stop/control," but also "the rising/expansion of breath"). Pranayama is mainly related to yoga, but it is used in a number of different meditative practices (Jerath et al., 2006). The aim of this work is to describe the state of the art relating to breath control, in order to develop an initial neurophysiological model of breathing techniques, and to explain how these techniques are able to induce altered states of consciousness in humans. Among the Pranayama techniques that comprise slow and controlled respiration, the most relevant are Nadi Shuddhi Pranayama (slow alternate nostril breathing), Pranava Pranayama (slow and deep breaths with the air flowing through the inferior, the middle and the superior thorax), Bhramari Pranayama (slow exhalation with nasal sounds similar to a wasp buzzing), and Sama Vritti Pranayama ("square breathing" with respiratory phases of equal duration). This paper will cover two fundamental aspects: 1) what are the physiological mechanisms behind the psychophysiological effects of breathing techniques; and 2) what is the relationship between breathing practices and consciousness states.

PSYCHOPHYSIOLOGICAL MECHANISMS OF BREATHING TECHNIQUES

We start to delineate a neurophysiological model of respiratory techniques and its effects on brain activity and the state of consciousness by briefly describing all factors that, in our opinion, are naturally involved during breathing techniques and are crucial to induce meditative states of consciousness:

1. The slowing down of respiratory frequency
2. The use of focused, sustained, voluntary top-down attention on the task
3. The rhythmic mechanical stimulation of the nasal epithelium during nasal breathing.

1. Slow respiratory frequency

In recent years, increasing scientific works have investigated the effects of slow breathing on animal and human physiology. A fundamental role is given to the peripherical changes in the body, due to increased dominance of the parasympathetic nervous system. A number of reviews have been published on the topic, systematically describing the physiological basis of these processes, and focusing on the importance of vagus nerve activity (Brown and Gerbarg, 2005; Streeter et al., 2012; Brown et al., 2013; Gerritsen and Band, 2018). Pathways involved transmit interoceptive information from the organism, in particular from the pulmonary (see Jerath et al., 2006), cardiovascular, and gastrointestinal systems, to cortical areas via projections of the nucleus of the tractus solitarius, and the parabrachial nucleus. Slow breathing is also directly related to modulation of the locus coeruleus, which is an important link between breathing rhythm and other brain areas related to arousal, attention, and emotional expression (Sheikhbahaei and Smith, 2017; Yackle et al., 2017). All these modifications induce also positive effects at the level of cognition and affective state, inducing relaxation and reducing anxiety, as well as increasing quality of life and wellbeing (Zaccaro et al., 2018a). However, these data are not very informative regarding (and never investigate) the induction of different states of consciousness.

2. Focused attention

Due to the difficulty of maintaining voluntary attention to the breathing task, breathing techniques are naturally related to top-down processes like attention, working memory, and executive monitoring, which are related to activation of higher-order brain areas such as the fronto-parietal network (Gard et al., 2014). For this reason, breathing techniques share similar aspects with the practice of focused attention meditation (Samatha meditation; Wallace, 2006). Focused attention meditation is related to the ability of continuously monitoring a very specific target (i.e. respiration), inhibiting the distractors, and reorienting one's attention to the target (Lutz et al., 2008; Hasenkamp et al., 2012), in order to develop progressive meta-awareness of mental processes (Vago and Silbersweig, 2012). A brain network modulated by focused attention meditation is the so-called default-mode network, comprising medial prefrontal and posterior cingulate cortices, which shows decreased activity during the practice (Brewer et al., 2011), associated with a reduction of mind-wandering. On the other hand, anterior cingulate cortex activity increases, meaning increased ability to focalize the attention, and monitoring conflictual mental contents (Holzel et al., 2007; Tang et al., 2010). At the EEG level, focused attention meditation is related to significant increases of alpha power and coherence (Travis, 2001; see Lee et al., 2018), generally interpreted as "relaxed alertness" and increased attentional processing of internally (i.e. bodily) generated stimuli (see Knyazev et al., 2011; Lomas et al., 2015). Focused attention meditation is also related to increased theta power (Takahashi et al., 2005; Dentico et al., 2016), associated with internalized attention and deep relaxation, and increased gamma power, index of conscious attention, sensory awareness, and perceptual clarity (Lutz et al., 2004; Cahn et al., 2010; Berkovich-Ohana et al., 2014; Braboszcz et al., 2017). Taken together, these results indicate that focused attention meditation alone is able to induce strong psychophysiological effects, and it is plausible that breathing techniques share same or similar neurocognitive circuits with it. However, there is another important, yet less investigated factor involved in breathing practices.

3. Rhythmic mechanical stimulation of the nasal epithelium

Breathing techniques, both of eastern or western derivation, prefer the involvement of nasal breathing route to the mouth (Ramacharaka, 1903; Iyengar, 1985; Jerath et al., 2006; Zaccaro et al., 2018a). A common (and easier) answer is that nasal breathing is more "spontaneous" than mouth breathing, or that it is more comfortable. However, spontaneity has never been one of the main concerns of breathing practices, often involving focused, hard and deep effort to control breathing phases, and requiring years of practice. Second, there are breathing techniques that use the mouth as preferred respiratory route (e.g. Sitali and Sitkari Pranayama) that are not related to subjective discomfort but, on the other hand, to increased relaxation and "cooling" of the organism (Telles and Naveen, 2008; Thanalakshmi et al., 2014). Looking at the Indian literature, we read that "only once the nostril channels are free, the yogi becomes able to control the Prana" (Hatha Yoga Pradipika), so the nostril channels are of great importance in controlling the vital energy of the organism. The existence of a mechanism present in the nostril, and not in the oral cavity, may be therefore hypothesized. Looking back in western scientific literature, it is possible to find an indication of its existence in the studies of the Nobel Prize winner Lord Adrian. In a series of studies, Adrian found that the simple passage of air into the nostrils caused a neural response in the olfactory bulb and in the piriform cortex, if the air flow pressure and speed were higher than that of natural breathing (Adrian, 1942; 1950; 1951). In the same years, Arduini and Moruzzi (1953a; 1953b) found specific electrical activities in the olfactory bulb in the "*cerveau isolé*" cat, by blowing unfiltered air into one or both nostrils. Again, Alan Hobson (1967) observed that air flow through nostrils had a synchronizing effect on the EEG of the frog. These results may be explained by nasal epithelium receptors that respond to mechanical stimuli. With "mechanical" we mean that they respond to non-chemical, odorless stimuli, induced by the airflow pressure. Recent studies have confirmed that "sniffing" is not just responsible of the transportation of the odoriferous chemical stimulus, but is itself part of the stimulus, as it specifically stimulates the mechanoreceptors of the nasal vault. Sniffing affects the perception of the intensity and quality of the odor, and it is sufficient to evoke a response in the pyriform cortex even in absence of odor (Buonviso et al., 2006; Kepecs et al., 2006; Mainland and Sobel, 2006). These first findings were brilliantly expanded by Fontanini and colleagues (2003; Fontanini and Bower, 2005; 2006). In anesthetized mice, they found that oscillatory activity in the olfactory bulb and pyriform cortex strongly correlated with the breathing rhythm, and that this pattern was disrupted with tracheotomy, when the air did not pass through the nostrils. Notably, in tracheotomized mice, nasal respiration-driven neuronal oscillations were restored via rhythmic artificial nostril stimulation with odorless air-puffs (Fontanini et al., 2003). In a final review, Fontanini and Bower (2006) explained that this synchronization may spread starting in the nostrils, causing a periodic activation of the olfactory epithelium due to the stimulation of the intranasal mechanical receptors. Then this oscillatory activity propagates to the olfactory bulb, and from there to areas connected to it, as the pyriform cortex, entorhinal cortex (Biella et al., 2001), amygdala (Cinelli et al., 1987; Price et al., 1991; Homma and Masaoka, 2008) and orbitofrontal cortex (Wilson and Mainen, 2006). This global synchronizing mechanism, hypothesized in 2006, is now considered a fact, having been found and deeply analyzed multiple times up to now. Starting from studies in frogs and turtles in the 70s (Servit and Strejckovà, 1976; Servit and Strejckovà, 1979; Servit et al., 1981), several recent studies showed that nasal respiration can drive neuronal oscillations in a vast number of non-olfactory areas, both subcortical and cortical, which comprise the olfactory bulb, the thalamus, the hippocampus, the amygdala, the insula, and the piriform, orbitofrontal, medial prefrontal, anterior cingulate, somatosensory, parietal, and occipital cortices (see Tort et al., 2018 for a recent review). Moreover, nasal respiration-driven neuronal oscillations are almost totally abolished (near 80-90%; Ito et al., 2014) via nostril bypass through tracheotomy (Fontanini et al., 2003; Ito et al., 2014; Yanovsky et al., 2014; Lockmann et al., 2016; Zhong et al., 2017), lesions of the olfactory epithelium (Moberly et al., 2018), inhibition of the olfactory bulb with designer drugs (Liu et al., 2017), and olfactory bulb surgical removal (Ito et al., 2014; Biskamp et al., 2017).

This mechanism has been discovered also in humans, when Kristof et al. (1981) found that nasal hyperventilation elicited paroxysmal abnormalities at the EEG level. Moreover, a study by Sobel et al. (1998) found with fMRI that sniffing odorless air induced activation in the piriform cortex and in medial and posterior orbitofrontal cortices. In this context, a ground-breaking contribution to the investigation of non-olfactory, higher-order functions of nasal breathing in humans was made by Zelano et al. (2016), who adopted intracranial EEG (iEEG) in epileptic patients, and found that nasal respiration-related oscillations in the piriform cortex, the amygdala and the hippocampus, were abolished during mouth breathing. Moreover, the inspiratory phase of nasal respiration was specifically related to improved performance in emotional recognition and episodic memory tasks. In addition, in the same year, Heck et al. (2016) demonstrated with iEEG that, in humans, nasal respiration-related oscillations can spread over frontal, temporal, and parietal cortices (for reviews see Heck et al., 2017; Varga and Heck, 2017). Another crucial study by Herrero et al. (2018) extended prior observations by finding coherence between breath and iEEG signals across a widespread network of cortical and subcortical brain structures. Most importantly, the authors found that: 1) iEEG-breath coherence increased in a frontotemporal-insular network during volitionally paced breathing; and 2) iEEG-breath coherence increased in the anterior cingulate, premotor, insular, and hippocampal cortices after paying voluntary attention to the breath. These last findings are particularly interesting, because they show that the effects of mechanical stimulation of the nasal epithelium are not independent from mental factors (e.g. focused attention), and they suggest the existence of a dynamic interaction among respiratory frequency, mechanical stimulation of the nasal epithelium, and focused attention. In conclusion, all the above-mentioned data may be considered to tentatively build a neurophysiological model of breathing techniques, relying on the interaction between its factors that induces the alteration of the state of consciousness.

ALTERED STATES OF CONSCIOUSNESS INDUCED BY BREATHING TECHNIQUES

The study of consciousness is a relatively new topic in human neuroscience, but it is receiving increasing interest from the philosophical, psychological, and neuroscientific communities (see Laureys et al., 2015; Schneider and Velmans, 2017). A state of consciousness is defined as the relationship between the "qualities" of consciousness (e.g. vision, sound, emotions, memory, thoughts etc.) in a particular moment, which is usually recognizable by who is in that state, and that strongly affects the way the individual interacts with the world (Revonuso et al., 2009). All deviations in the functioning of consciousness from the ordinary, common state (e.g. during sleep, dreaming, or meditation) are considered altered states of consciousness (Tart, 1975). The neural correlates that sustain a state of consciousness are those mechanisms that are jointly sufficient for being conscious in a broad sense, supporting the emergence of conscious experience itself (i.e. as a whole, irrespective of its contents), and they depend on a complex and dynamic capacity of the central nervous system to integrate a vast number of information, thanks to temporal and spatial interactions in cortical and subcortical systems (Koch et al., 2016; Northoff and Huang, 2017).

As described above, breathing techniques are capable of inducing oscillations that spread over distant, non-olfactory areas, and that reorganize spatio-temporal features of the brain related to ordinary (wakefulness) and altered states of consciousness (i.e. NREM and REM sleep, anaesthesia, meditation, and psychedelic states) (Northoff and Huang, 2017; Atasoy et al., 2017). In this context, a recent study (Piarulli et al., 2018) adopting high-density EEG found that ultra-slow passive mechanical stimulations of the olfactory epithelium via odourless air-puffs is able, alone, to induce an unusual state of consciousness, described by participants as different from their ordinary state, and characterized by inwardly directed attention, altered experience of the body and of the passage of time, reduction in volitional control of thoughts, and decrease in rational thinking. These subjective effects were sustained by a widespread increase of delta and theta EEG power over the neocortex and, in particular, in medial prefrontal cortices and in structures involving the default mode network. These effects alone do not completely cover the full spectrum of neurophysiological effects related to breathing practices (for example, slow breathing techniques in naïve subjects are mainly related to increase in alpha EEG power and decrease of theta EEG power; Zaccaro et al., 2018a), but indeed they show an important role of slow stimulation of nasal epithelium in modifying the state of consciousness.

Starting from this literature, there are two scientific experiments in progress that are directly investigating the role of the factors involved in slow breathing practices, aiming at disentangling the effects of mechanical nasal stimulation from those attributed to parasympathetic activity (slow respiratory frequency), and to modulation of higher-order cognitive functions (focused attention). The first is analyzing EEG activity in skilled meditators, performing two sessions of the same slow breathing technique (Sama Vritti Pranayama), one performed breathing through the nose, and one performed breathing through the mouth. The second is analyzing fMRI brain activity and functional connectivity in naïve subjects comparing mechanical stimulation of olfactory epithelium to voluntary breathing exercises. Both studies are focusing also on the subjective experiences of participants, adopting phenomenological retrospective assessment methodology as the Phenomenology of Consciousness Inventory (Pekala, 1991). Preliminary results are showing that breathing techniques have totally different effects depending on whether they are performed through the nose or through the mouth, and that nasal stimulation has similar but different psychophysiological effects depending on whether it is passively (via mechanical stimulation) or actively (via slow nasal breathing) induced (see Zaccaro et al., 2018b; Zaccaro et al., 2019).

To date, it is only possible to speculate on the neurophysiological mechanism behind slow nasal breathing, that future studies will confirm or refute. In our opinion, a fundamental role is played by the interaction between respiratory frequency, top-down attention, and mechanical stimulation of the nasal epithelium. We speculate that the fine-tuned modulation driven by breathing on the interaction between high-order cortices (in particular, in medial prefrontal cortices and in structures involving the default mode network) and subcortical structures (e.g. locus coeruleus) is possible only if it is associated to rhythmic oscillations arriving from the olfactory bulb, dependent in turn from nasal mechanical stimulation (Fontanini and Bower, 2006; Tort et al., 2018; see also Melnychuk et al., 2018), and that this interaction is affected, if not totally abolished, by mouth breathing. We consequently consider the complex interactions between the nasal breathing route, respiratory frequency, and top-down attention, as the fundamental triad associated to meditative states of consciousness in humans during breathing practices like Pranayama.

Traditionally, Pranayama has been long-time considered an inner "door", an alert but relaxed state of consciousness ideal for developing more deep, meditative, and mysterious states of consciousness, that future studies should address (Vieten et al., 2018). New tools and techniques are urgently needed in order to investigate first- and third-person related aspects of states of consciousness, as empirical-phenomenological, neurophenomenological and micro-phenomenological approaches (Pekala, 1991; Varela et al., 1991; Petitmengin, 2017). Avoiding a reductionistic approach, we can conclude that nasal stimulation during slow breathing is fundamental for reaching meditative states of consciousness, and further research should investigate the complex and interactive relationship between the factors involved in breathing techniques.

1 Department of Surgical, Medical and Molecular Pathology and Critical Care Medicine, University of Pisa, Pisa (PI), Italy
a.zaccar090@gmail.com
2 Department of Psychology and Cognitive Science, University of Trento, Rovereto (TN), Italy
gabriele.penazzi92@gmail.com

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