iStim. A New Portable Device for Interoceptive Stimulation

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Abstract. The sense of the physiological condition of the entire organism (i.e. interoception) represents a fundamental perception that serves a correct and balanced functioning of the human body. Interoceptive information constitutes a core element in a variety of psycho-physiological systems and processes; therefore the possibility to consistently stimulate the interoceptive system with specifically targeted inputs has a fundamental value both in assessing and clinical settings. The article illustrates a new technological portable device able to delivered precise interoceptive parasympathetic stimuli to C-T afferents connected to the lamina I spinothalamocortical system. Interoceptive stimuli can be programmed in a variety of parameters, ranging from continuous stimulation to modulation of frequency and variance. Implications and possible applications are discussed in both assessing protocols and clinical treatments as well.

Keywords: Interoception · Interoceptive stimulation · C-Touch
C-fibers · Affective touch

1 Introduction

Interoception represents an emerging and promising topic in Neuroscience. Interoceptive perceptions can be defined as the sense of the physiological status of the entire organism [1] and they encompass a broad range of relevant biological functions that serve conscious and unconscious processes.

The central component of the interoceptive system is the anterior insular cortex (AIC) that receives information through a vast network of small un-myelinated fibers connected to the Lamina I spinothalamocortical pathway. These specific fibers, called C-Fibers compose a poly-modal afferent system that innervates the entire organism and report a wide range of inputs such as: hunger, thirst, pain, itch, temperature [2], muscle contraction [3, 4], hormonal and immune activity, cardiorespiratory function [1, 5], along with a specific type of tactile perception called C-Touch [6]. These inputs are processed in the interoceptive matrix that creates a metarepresentation of the organism's active processes also according to an explicit lateralization of the cortex. Specifically, the left and the right insula are usually coactive in the interoceptive system

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nonetheless, parasympathetic inputs are preferentially processed by the left insula [7] while sympathetic ones are usually processed by the right one [1, 8]. In the last decade, interoception emerged as a promising field of study due to the relevant meaning that interoceptive information has to the functioning of the organism. Recent evidence identified interoceptive altered processes in a broad range of clinical condition such as chronic pain [9], eating disorders [10–13], anxiety [14, 15], depression [16–20], addictions [21, 22], post-traumatic stress disorder [23], insomnia [24] and several others conditions [25, 26]. However, a primary limitation in the study of interoceptive system is the ontological difficulty to access and reproduce specific interoceptive stimuli. Albeit it is quite easy to activate pain and temperature inputs, other interoceptive stimuli (e.g. hunger, thirst, visceral sensations) are quite difficult to reproduce in a controlled manner, prejudicing the possibility to consistently explore different aspects of the interoceptive system in controlled settings. Moreover, easily reproducible interoceptive input, such as pain and temperature, are generally processed by the right insula [27, 28] due to their sympathetic high valence, leaving the whole system of parasympathetic input vastly unexplored.

Parasympathetic interoceptive input has been recently discovered as a promising research field. Among these kind of stimuli, C-Touch (or affective touch) is arguably the most interesting parasympathetic interoceptive input. C-Touch afferent fibers constitute a secondary touch system with a deep involvement in different psychophysiological pathways [29]. A prominent theory suggested their fundamental role in social contact and emotional bonding [30], moreover recent evidence demonstrated that interoceptive C-Touch can modulate body ownership and embodiment [31]. Additionally, several clinical conditions demonstrated altered perception connected to C-T afferents, suggesting implication of interoceptive touch also in psychopathological functioning [32].

Several experimental devices [31, 33–35] actually exist and are able to delivered interoceptive C-Tactile stimulation. Nonetheless, these instruments suffer from several limitations. Specifically, they are usually unable to deliver continuous stimulation and they are not able to modify the frequency and the variance of the stimuli. Moreover they usually require a fixed setup, limiting the portability of the instrument in different settings (i.e. hospitals, laboratories) and the possibility to apply stimuli to different body parts of the subject. To address these issues, the paper proposes a new technological portable device specifically designed to deliver tactile interoceptive stimuli, allowing continuous stimulation to any chosen body site along with the ability to program variance and frequency of the delivered stimuli.

2 Technical Development

The interoceptive stimulator has been designed and developed to provide continuous C-Tactile stimuli with a programmable pattern of stimulation. To pursuit this goal, the device has been designed taking in consideration all the relevant factors connected to C-T afferent fibres.

C-T fibres constitute a secondary touch system with very peculiar characteristics. They are uniquely found in not glabrous skin where they distinctively respond to light touch with a force under 2.5 mN [36, 37] and a stroking velocity between 1 and 10 cm/s [31, 38] with a mean peak of activation around 3 cm/s. Moreover they exhibit a tendency to fatigue [6, 39] and a specific after discharge pattern with a delayed acceleration effect [36, 40]. Considering these factors, the device (Fig. 1) uses a step motor, a driver, and an ARDUINO NANO as main programmable controller to deliver targeted interoceptive C-Tactile stimuli.

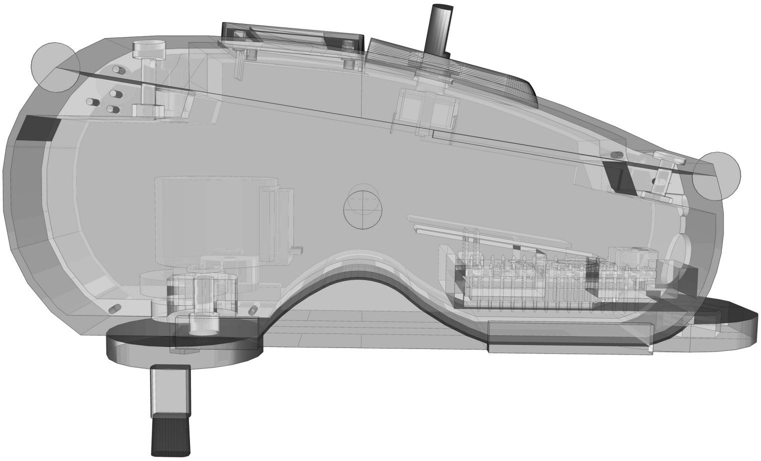

Fig. 1. Interoceptive portable stimulator with 3D printed case and calibrated probe mounted.

A LCD and a digital encoder allow selecting pre-programmed stimulation patterns directly on the device. A rechargeable battery connected to a DC Boost ensures different lines to power the step motor (12 v) and the main electronics (3 v–5 v). The device is enclosed in a specific 3D printed case that allows portability and manoeuvrability. A specifically designed and calibrated probe is attached to the step motor main shaft, providing tactile stimulation. The probe moves in circular pattern, with a linear component handled by the operator. Mixing circular and linear stimulation (Fig. 2), the probe matches the maximal mean firing frequency of CT afferents (3 cm/s ± 0.5 cm/s) [33] allowing continuous stimulation with a specific pre-calibrated force < 2.5 mN that is the optimal threshold for interoceptive touch [36, 41, 42]. Lastly, the probe oval shaped area matches the receptive CT human afferent patch ($\approx$35 mm^2) [39, 43] ensuring a targeted interoceptive stimulus.

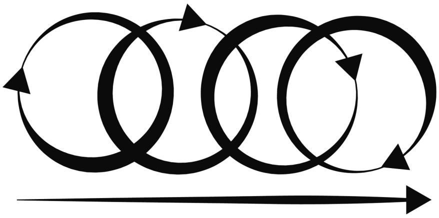

Fig. 2. Pattern of stimulation with circular and linear components.

Moreover, C-Tactile afferents show a specific behaviour of fatigue and inexcitability [6, 39] reducing their firing rate to 0 after 5 s of continuous stimulation [43], therefore the device factored several patterns of stimulation for optimal continuous performance. Mixing linear and circular stimulation, considering probe dimension, optimal velocity, and angular motion, the device fires a single CT afferent patch only for 0.28 s within a single revolution, allowing continuous stimulation without inhibition of the receptive CT field.

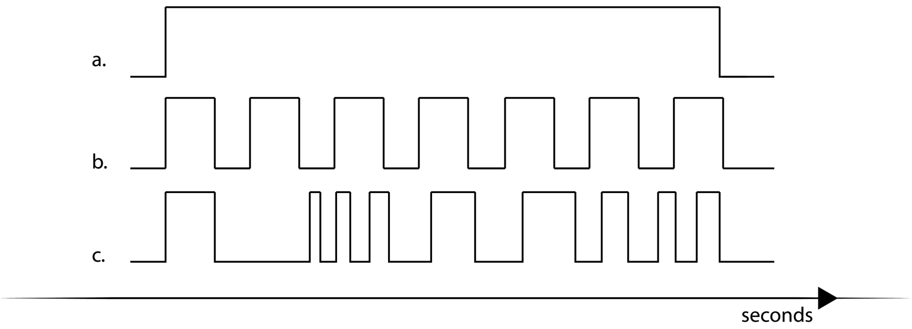

Fig. 3. Examples of programmable stimulation. (a.) continuous stimulation (b.) low variance stimulation (c.) high variance stimulation

The device is programmed with ARDUINO IDE native language. It uses common open source libraries for the digital encoder and the LCD screen. A custom library for the stepper motor driver has been developed to reduce motor time activation; the shaft can therefore reach a specific angular velocity within only 10 ms, providing almost instantaneous interoceptive stimulation in the optimal CT firing range.

The code can be updated via USB and specific stimulation patterns can be uploaded in the memory of the device and selected through the digital encoder and the LCD. The device stores stimulation patterns as `STRING` variables in the `PROGMEM` allowing the microcontroller to maintain memory also without power. A set of parameters can be controlled, such as: velocity, duration of stimulation, and pattern of stimuli. These parameters can be mixed together creating different types of interoceptive parasympathetic stimulation with various purposes.

In continuous mode (Fig. 3a) the devices activates a continuous interoceptive stimulus. Duration of the stimulation can be programmed and stored in flash memory or the device can be stopped at the appropriate time via a coded command selected through the digital encoder.

In variance stimulation (Fig. 3b and c) a predetermined pattern of stimuli with defined optimal velocity and durations is programmed in the device and selected thought the digital encoder. If selected the devices activates a series of stimuli in a fixed sequence that can be customized either for the duration of a single stimulus, the duration of the pause between stimuli, or both. Sequences can be therefore either programmed to deliver a low variance stimulation (Fig. 3b) where the device presents interoceptive stimuli with a predictable pattern; or the device can be programmed to deliver high variance stimulation, presenting a pattern of stimulation with a low predictability. Possible application of these to kind of stimulation will be presented in the discussion section.

Lastly, the device implements a SPI port that allows synchronization of stimuli between clone interoceptive stimulators in a `MASTER-INDEPENDENT SLAVES` configuration up to 256 devices, or in a `DAISY CHAIN` configuration for a larger number of cloned devices.

3 Discussion, Applications, and Conclusions

In the paper we presented a new portable device able to deliver interoceptive parasympathetic programmable stimulation. The device, entirely developed by D.D.L., has already been used to assess subclinical conditions connected to anxiety and eating disorders [44]. Moreover, C-Tactile stimuli have been proved to modulate pain [43, 45] and anxiety [43], therefore the device may show applicability in clinical conditions that require treatment both on clinical and subclinical level [44, 46, 47].

Furthermore, parasympathetic interoceptive tactile stimuli can provide a powerful instrument to assess body perception, providing a new assessment protocol able to explore the role of the body inner perceptions in different conditions.

Specifically, coactive processes in the right and left insula can be used as behavioral indexes of sympathetic and parasympathetic balance. A theoretical protocol that asks the subject to estimate the parameters of a CT parasympathetic stimulus (i.e. duration in seconds) can investigate distortions in bodily perception, indicating the presence of an alteration in the processing of the information arising from the body. In more details, according to Craig [8] a dominance of sympathetic stimuli (i.e. pain, anxiety, etc.) should distort the perception of CT stimuli duration, which should be perceived longer than real. Conversely, clinical conditions that are connected to low bodily information processing (i.e. depression, anorexia nervosa) should produce distortions in perception of CT stimuli in an opposite direction. This information might therefore be used to probe body perception and body perceptive distortions in clinical and healthy subjects.

Lastly, the device allows a complete control upon several key variables. It can be therefore programmed to deliver low or high variance stimulation with specified learning rate curves. Different variance stimulation with programmed learning rate curves has been implemented as a method to promote neuroplasticity in several applications [48]. The device might therefore utilize the same rationale to promote or suppress neuroplasticity in the interoceptive matrix. This kind of application can be theoretically applied to a variety of clinical conditions. Specifically, chronic pain, addictions, PTSD, and insomnia present hyper-activation in the cortical areas linked to the interoceptive matrix [23, 24, 26–28, 49], therefore a low variance stimulation able to reduce neuroplasticity might reduce the processing of sympathetic high arousal interoceptive stimuli in the right insula, improving clinical conditions and decreasing symptoms severity.

Conversely, a high variance stimulation aimed at enhancing interoceptive neuroplasticity can provide application in those conditions that are characterized by a low processing of bodily sensations and a functional and structural reduction of the interoceptive cortical areas, such as depression [16–19], anorexia nervosa and other eating related disorders [10–12].

Lastly, the device can also be used in complementary manner along with other technologies such as virtual reality (VR) [50], sonoception [51], and "positive technologies" [52] on a general level. For example, it can be used to improve embodiment and body ownership [31] in VR environments for clinical and assessing purposes, to modulate specific interoceptive patterns for treatments [50], or to provide interoceptive stimulation during a variety of other contexts as well (i.e. exposure therapy). These examples summarize some of the possibilities of the interoceptive stimulator, nonetheless promising evidence in the field of interoception suggests that other practical applications might be developed in future.

Author Contributions

Conceptualization, D.D.L.; Writing – Original Draft, D.D.L; Writing – Review & Editing, G.R., and P.C.; Hardware and software development: D.D.L.; Supervision G.R., and P.C.

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