Understanding Interoception and Its Importance in Body and Mind Functions: A Review

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***Abstract*—Interoception, the sensing of the body's internal sensations, contributes to numerous aspects of human's cognitive and affective abilities. Interoception mechanisms ensure physiological health through the coordination of homeostatic reflexes and allostatic responses. This review presents how deeply interoception controls our daily motivational behaviors and associated affective and emotional feelings. Since its discovery at the twilight of the 19th century, relentless research and experimental work have pushed far back the borders of interoception. Concept enrichment is still to find its limits: from its role in balancing and maintaining the energy-efficiency of the integrity and health of the body (homeostasis) to its emotional importance in learning, motivation and decision making, the field of interoception doesn't stop extending. Scientific measuring of interoceptive effects is also making fulgurant progress, though accuracy and relation between self-awareness and interoceptive attention are still to be fine-tuned. In addition, the review also addresses impairment caused by interoceptive deficiencies (alexithymia), commenting research and group experiments made in physical, emotional and physiological fields. Open questions are raised about whether interoception is a unitary function as well as about the ways to reduce individual weak interoceptive abilities, such as training and meditation. In conclusion, the signaling, sensing, and detection of bodily states are implicated in physical and mental well-being. Interoception research contributes to understanding into the dynamic interactions between body, brain, and mind.**

***Index Terms*—Interoception, homeostasis, interoceptive accuracy/attention, alexithymia**

I. Introduction

The essential functionality of the brain is to keep itself as well as the rest of the body alive. The brain coordinates the governance of vital internal processing, including blood pressure, breathing, and digestion by flexible reaction to external and internal changes. Interoception refers to the sensing and regulating the body's internal state, processing the afferent and efferent channels of the interplay between body and brain, which allows homeostasis (state of physical stability) through covert reflexes, motivational drivers, and express body sensations [1]. Interoception is differentiated by focusing on internal body milieu from exteroceptive senses that process information from the external environment, such as vision and audition, and more proximate senses that use the body to describe the outer world and the relation to it, such as proprioception, touch and taste. Interoceptive mechanisms ensure physiological health though the brain coordination of homeostatic reflexes and allostatic (stability through variation to anticipate the needs) responses, including associated affective and emotional feelings as well as motivational behaviors. A comprehensive understanding of homeostasis, emotion, cognition, and overall well-being shall incorporate the understanding of interoception. Interoceptive processing plays a significant role in health and disease.

This article reviews the scope evolution of interoception, and approaches to its quantification, discusses the contributing role of interoception in homeostasis, emotion processing as well as learning, motivation and decision making. Next, the review addresses impairment caused by interoceptive deficiencies (alexithymia), commenting research and group experiments made in physical, physiological and emotional fields from deficits of affective and emotional feelings to learning, reward and decision making. Finally, two outstanding questions are discussed, whether interoception is a unitary ability and how interoception abilities can be improved.

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II. What Is Interoception?

A. Original

Interoception was first coined by Charles S. Sherrington, a preeminent Bristish neurophysiologist. Originally, Sherrington used this term to refer to sensory inputs from the internal body, especially the visceral organs. Interoception was differentiated conceptually from exteroception, which referred to sensory inputs from the external environment outside of the body, and other sensory inputs. According to Sherrington's definition, there were a number of sensory inputs, such as proprioception, teloreception, chemoreceoption, thermoreception and nociception. Proprioception is the signals related to limb position, and teloreception is sensory inputs activated from a distance, such as vision and audition. Chemoreception refers to taste and smell, and thermoception refers temperature. Nociception is sensory inputs activated by physical damages or threatening stimuli. Motoric reflexes, which were also coined by Sherrington, were used to measure these input signals.

Thermoreception and nociception along with the sense of touch were categorized by Sherrington as parts of exteroception. All of these three were discriminative cutaneous sensations. Numerous researchers held the same thoughts that exteroceptive sensory inputs coming from the skin were activated by the external environment.

B. Concept Enrichment

Homeostasis is an on-going process that comprises organized interactive functions, which dynamically maintain an optimal balance of the body in both good health and illness. Being the biggest organ of the body, the skin has significant functions in homeostasis, such as keeping balance of water and electrolyte, regulating body temperature and producing

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vitamin D. AD Craig, an American functional neuroanatomist found that most sensory receptors in the skin have small-diameter fibers, which actually signal the condition of the skin itself [2, 3]. Along with the sensory input from the viscera, the small-diameter sensory inputs from skin and muscle provide the ongoing sensation information to homeostatic control of changes in cardiovascular and respiratory systems. In contrast, the sensory inputs from the skin, which have large-diameter fibers and cell bodies, convey mechanical signals activated by external stimuli, such as pressure, velocity, stretch or vibration. The signals, which represent changes in force, length and position from muscle and joints, are produced by skeletal muscle. The dorsal column-medial lemniscal pathway processes large-diameter sensory inputs, spinothalamic pathway processes small-diameter sensory inputs differentially.

Craig showed other facts supporting the reason why thermoception and nociception would belong to interoception [4]. All thermoceptive sensors and most nociceptive sensors in the skin can be activated by a condition change, either exogenous or endogenous. In contrast, cutaneous mechanical receptors can be activated by external forces only. As it can be cooled down by the environment temperature, the skin also can be cooled quickly by a blood flow reduction caused by autonomic vascular constriction. The small-diameter axons immediately sense these changes and provide feedback signals to homeostasis to regulate body temperature. Similarly, almost all nociceptors can be activated by changing the skin's metabolic conditions in addition to the external physical damages. For example, both the pH value and inflammation caused by chemicals can cause pains. In contrast, the large-diameter mechanoreceptors at the base of a hair follicle can be activated only when the hair is flicked quickly enough by an external object.

Craig's research also demonstrated that a distinct interoceptive cortex, which includes the primary cortical representation for both thermorecpetion and nociception, provides substance for the fundamental distinctness of interoception [5]. The evidence indicated that the dorsal posterior insula represents nearly all aspects of the body's physiological condition, which are signaled by small-diameter fibers, such as temperature and pain. Other researchers who studied taste also recognized that the anterior insula is involved in subject judgements of sensation [6]. They showed in their critical experiments that the primary taste cortex lies in the dorsal middle and posterior insula. Craig claimed that a complete interoceptive cortex exists in the posterior one-third of the dorsal insula, including both a posterior half that receives input from the VMpo and an anterior half that receives VMb input. This region serves as primary sensory cortex for all distinct bodily feelings that an individual can perceive, such as cool, warm, itch, pricking pain, burning pain, sharpness and taste. The region also supports to underlie the less well discriminated interoceptive feelings from the body, such as muscle burn, joint ache as well as the visceral feelings of fullness, hunger, thirst and "air hunger". The visceral stimuli and vascular distention reported as "pressure" can activate that region as well.

Therefore, the concept of interoception was enlarged to include small-diameter sensory inputs from the whole body, from viscera, muscle, joints and skin. Thermorecpetion and nociception are removed from exteroception and added to interoception because they represent the physiological condition of the body which are conveyed by small-diameter sensory fibers and the spinothalamic pathway to the interoceptive cortex.

C. Bidirectional Signal Processing

More recently, interoception refers to the representation of the internal body states, which more accurately reflect the bidirectional signal processing between the brain and the internal organs [7]. In this description, interoception includes the processes by which an internal organ senses, interprets, integrates and regulate signals from and within itself. According to the Fig. 1, sensing action is the communication from internal organs in physiological conditions to the brain, whereas regulating action is the communication from the brain to internal organs. The processing signals of the internal environment include not only components of automatic viscera, temperature and pain, smell and taste, but also components of automatic vascular, neuroendocrine and neuroimmune systems.

Interoceptive signals originate from within an internal organ. Interoceptors are sensors and receptors in neurons that detect various interoceptive signals and transform them into electrical, hormonal, or other non-neural signals, which are integrated and interpreted by the brain. The location of Interoceptor determines which homeostatic pathway the interoceptive signals are transmitted, either spinothalams pathways for small-diameter fibers or cranial/vagal pathways for the nucleus tractus solitarii (NTS). These signals are interpreted, integrated and processed by central interceptors and integrators of interoception. They are primarily processed in the posterior and medial regions of insula and then reach the anterior insular cortex where they build the connection with emotion and cogntion. The human insula is activated when an individual consciously participates in its interoceptive states, which severs as a key interoceptive hub for integrating and regulating interoceptive signals from the internal body milieu and external environment.

The concept of regulating interoception through descending pathways is considered to be incorporated into interoception. The primary function of the regulatory signals of interoception is to regulate the generation and transmission of interoceptive signals on the target body organs. However, it is a big challenge to identify and measure the impact of the regulatory signals on the target body organ. That shall be one possible direction for future research.

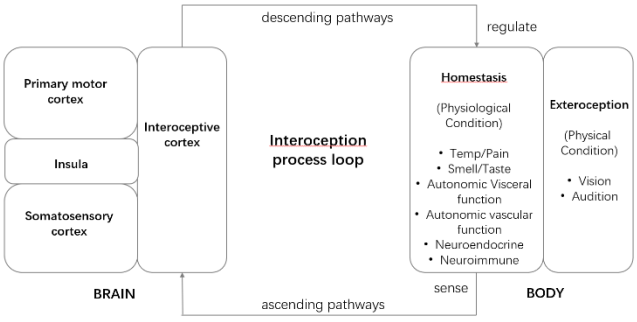


Fig. 1. The processing signals of the internal environment.

D. Four Levels of Awareness for Interoception

There is a debate concerning the level of the cognitive representation for interoception [8]. At the first level, homeostatic control involves interoception without the

individual's conscious awareness. For instance, the insulin releases at detecting in the blood a glucose spike. At the second level, an individual is consciously aware of the changes of its interoceptive state when interoception occurs. At this level, an individual is able to recognize the interoceptive signal with conscious perception, but without explicit recognition. In other words, an individual can be aware of the changes of the internal state, but is unable to label the state. It may be aware of experiencing an unusual internal state, but is unable to know which specific interoceptive change it is. At the third level, an individual is able to detect the changes of its internal state and recognize the new interoceptive state, such as thirst, hunger, heat. At the final level, an individual is able to label verbally the new interoceptive state.

III. Why Is Interoception Important?

A. The Role of Interoception in Homeostasis

Interoception, as the perception of physiological condition of the body, supports homeostatic control and allostatic adaptation. Interoception ensures the organs homeostasis as well as drives behaviors through bodily feelings such as hunger, thirst and hunger of "air". Homestasis, which was coined by the physiologist Walter Cannon in 1932, is an on-going process that contains a set of organized interactive functions that maintain an optimal balance in the body. The effectors of homeostasis include neuro and endocrine, which are the two crucial elements in interoception. The goal of homeostasis is to balance and maintain the energy-efficiency of the integrity and health of the body [2,3,9]. The optimal utilization of energy is one of the fundamental principles of homeostasis. Almost half of the small-diameter sensory fibers from muscle sensing energy use of workload can be named energy sensors. Allostasis refers to the specific mechanisms used by an organism as it seeks to regain homeostasis.

Each person has a unique capacity for bodily awareness, which is called interoceptive awareness by researchers who are interested in cardiorespiratory and visceral sensory activity on human mood, emotion and behavior [2, 3, 9, 10]. The heartbeat awareness is commonly used as a quantifiable capacity of a person's interoceptive awareness. Numerous researchers showed that an individual's heartbeat awareness correlates with their ratings of emotional feelings intensity, no matter it is positive or negative [2, 9, 11–15]. The better heartbeat perceivers are better at reading their emotional feelings. The one who is better at reading their own feelings is also better at reading others' emotional feelings.

A wealth of evidence of physiological and functional imaging on heartbeat awareness showed that anterior insula cortex is an essential site for feeling awareness, and interoception plays the fundamental role in human feelings [6, 14, 15]. Better heartbeat perceivers have better function at both emotional and cognitive level. In addition, research showed that better heartbeat perceivers expend less energy than poor heartbeat perceivers, which interpreted that interoceptive awareness enables better self-regulation of energy utilization [13].

Interoception is increasingly recognized to have an impact on cognition, influencing attention and perception, decision-making and emotion processing. As such, interoception is a complex phenomenon that presents several different dimensions. Interoceptive deficits are now recognized as important factors in anxiety and depression, addiction and eating disorder. Interoception is linked to body awareness and phenomenal consciousness, of which impact extends beyond homeostatic and allostatic reflexes and is proposed to be fundamental to self-awareness, emotion (affective feelings and behaviours), motivation, and social cognition [12].

B. The Role of Interoception in Emotional Processing

Most modern theories suggest that emotions are a combination of awareness of physiological arousal and cognitive appraisal of contextual cues. Therefore, interoception of arousal plays a crucial role in experiencing emotion since interoception is necessary for detecting emotional signals accurately and judging emotional intensity, which both are important to identify one's emotional state. Empirical evidence supports that interoception is necessary for all aspects of emotional processing, such as interoceptive accuracy's correlation with emotional ability, emotional intensity, emotion regulation and arousal focus [17, 18]. The better internal signals individuals perceive, the more intense emotional they can experience, the greater arousal focus they have at recounting the emotional experience.

Depression is associated with less intense emotions and consistent to the association with reduced physiological activity to positive stimuli, which makes it more difficult for perception of physiological reaction [19, 20]. Furthermore, specific internal states are linked with particular emotions, as existing correlation between disgust and cardiac and gastric activities, anger and increased heart rate and temperature, fear and surprise and increased skin conductance and decreased blood volume at each heartbeat. Overall, perception of non-affective interoceptive states seem to be correlated with perception of affective states which supports the hypothesis of intrinsic link between interoception and emotion.

For emotion regulation, interoceptive accuracy is specific benefit to use reappraisal strategy. Fustos and colleagues reasoned individuals with better interoception should be easier to regulate their emotions through reappraisal [18]. It enables earlier intervention to prevent consolidation and escalation of negative emotion. The more precise individualizing emotional states, the more targeted and more effective the intervention can enable [21]. Reappraisal is an effective method to regulate emotion when negative states are re-appraised cognitively, which are perceived as neutral or positive in order to limit the negative impact. It is reported that individuals with better cardiac interoceptive accuracy use cognitive reappraisal strategy and suppression on emotion regulation strategy more frequently than those who have poor accuracy.

Besides the correlation between interoception and self-focused emotion processing, evidence also shows that interoceptive abilities associate with one's responsiveness to others' emotion. Terasawa and colleagues demonstrated those who have better interoceptive accuracy had higher tendency to report experiencing emotional responses to others' emotional expression images [22].

C. The Role of Interoception in Learning, Motivation and Decision Making

It is intuitive that learning relies on interoception. Poor interoception may be characterized not only by failing to perceive internal signals, but also by failing to identify and discriminate between interoceptive signals [23]. Bevins and Besheer claimed that mis-categorization of interoceptive information may result in a noisy or inconsistent learning signal, systematic mis-classification of the punishment signals' internal source, and classifying a specific interoceptive signal which shall be evaluated as a negative one to a positive reward signal, such as pain, starvation or muscle damage [24].

It is also intuitive that motivation and decision-making is associated with interoception. According to classic theories, decision-making is to make a highest valued choice based on the value calculation for each give option. For physiological stimuli, such as food or water, the value of calculation result depends on one's current interoceptive state. For example, the higher the value of food, the more starving one is [23]. Therefore, it is essential to perceive one's interoceptive signals accurately in order to determine the value. In addition, decision-making is also relevant to the stored information of bodily consequences for stimuli and responses. This information is another source of value calculation for the given options.

The role of interoception in learning, motivation and decision-making was recognized firstly by Pavlove (1849–1936) in his work on classical conditioning associations. He claimed that interoceptive states can enter into, either conditioned or unconditioned stimuli and can affect the learning acquisition and expression by acting as contextual cues or occasion setters. The relationship between interoceptive accuracy and learning and decision-making was directly assessed by Werner and colleague in 2009. It was found that individuals with higher score in the heartbeat counting task had a better performance in the Iowa Gambling Task. Those people with better interoceptive accuracy were better able to perceive bodily cues and use them to for decision-making [25, 26].

The correlation between risky decision-making and interoception was studied as well. The results from the study done by Sokol-Hessner and colleagues confirmed that individuals with better interoceptive accuracy were more loss-averse, providing direct evidence for the association between interoception and risky decision-making [27, 28].

IV. How Is Interoception Measured?

A. A Big Challenge

As explained in Paragraph 1.4, interoception occurs at four levels: implicit homeostasis, signal conscious perception without recognition, signal recognition without verbal labelling and signal verbal labelling [23]. There are different ways to measure interoception. Thresholds measures detect a participant's presence or absence of sensation. Interoceptive load measures determine a participant's change in interoceptive capacity. Questionnaire measures reflect a participant's distinct interoceptive state with verbal label. However, the difficulties are how to identify relationships between different interoceptive measures (Heartbeat counting or muscle efforts) and different interoceptive dimensions (attention, accuracy and metacognitive abilities), as well as different measurement types (objective performance or subjective beliefs).

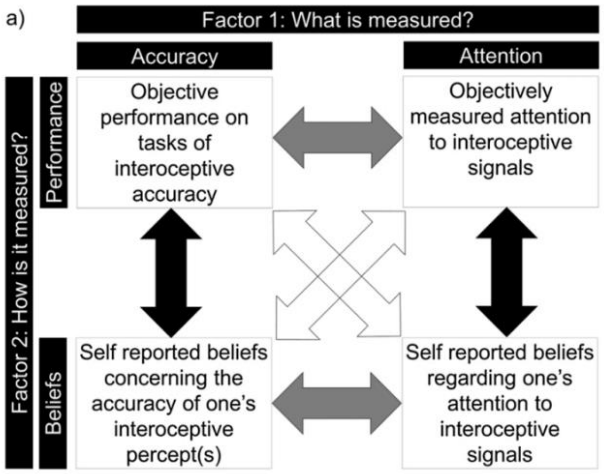
Heartbeat counting or discrimination are the exclusive measures commonly used in interoceptive accuracy studies. Although cardiac sensitivity tasks are extensively used, about 40% typical individuals are not able to consciously perceive their heartbeat. Furthermore, heartbeat can be perceived through touch, exteroceptive receptors due to the vibration in the chest. Heartbeat discrimination task is a preferred way to quantify interoceptive accuracy, because it is much less influenced by beliefs. However, this task also has its limitation, such as requiring to gain precise estimates of ability. In addition, scores on the heartbeat counting and discrimination tasks show modest correlation. In addition to heartbeat perception task measuring interoception, other measures have been used as well, such as gastric distention, detection tastes, intensity ratings of colon distension and thresholds for initial perception.

Besides measures of interoceptive accuracy, numerous self-report measures are used to assess self-reported interoception like interoceptive sensibility under the model of Garfinkel and Critchley (2013). These measures include the Body Perception Questionnaire (BPQ) [29], the Multidimensional Assessment of Interoceptive Awareness (MAIA) [30], the Body Consciousness Questionnaire [31], the Body Awareness Questionnaire [32], the Interoception Sensory Questionnaire [33], and the Self Awareness Questionnaire [34]. All these measures have limitation because subjective perception of interoceptive attention is often confounded with which interoceptive signals are present within the individual like BPQ or by assessing multiple aspects of interoception, such as MAIA and BCQ [35]. Confident ratings are used to qualify self-reported interoception in interoceptive accuracy tasks like heartbeat counting or discrimination procedures. However, these are not associated with self-report interoception questionnaires. Even though efforts are made to assess the relationship between self-report questionnaire measures and objective measures of interoception, findings are varied from studies.

B. 2×2 factorial Model

A well-known interoception model with three-dimension construct was proposed by Garfinkel in 2015, comprising interoceptive sensitivity, interoceptive sensibility and interoceptive awareness. Interoceptive sensitivity is the ability to accurately perceive the internal state of one's body, which is measured by performance on objective measures of interoception. Interoceptive sensibility is the ability to detect or discriminate the interoceptive signals, which are measured by confidence rating or questionnaires about self-reported beliefs of one's own interoception. Interoceptive awareness is a metacognitive measure, which reflects the correspondence between interoceptive sensibility and interoceptive sensitivity. Interoceptive awareness is also referred as interoceptive insight. Interoceptive awareness depends on the degree to how to accurately measure interoceptive sensitivity and interoceptive sensibility and how to combine these measures.

Murphy, Catmur and Bird (2019) suggested a 2×2 factorial model of interoception in 2019, a modified version of the three-dimensional model (Fig. 2). Their model highlights the significance of distinguishing between "how" interoception is measured, objective performance measures or via self-report beliefs, but also includes "what" is measured, attention or accuracy, in order to discriminate possible individual difference in interoception. The first factor is the target of measurement: accuracy and attention, the two major features of interoception. Accuracy refers to the degree to which one's perception is a true representation of the internal body state, while attention refers to the degree to which interoceptive signals are the attention object. The second factor is the type of measurement: objective or self-report. This 2×2 factorial model has four main measurements of interoceptive ability: (1) Objective measurement of accuracy of interoceptive perception, which is performance on objective measures of interoception, such as heartbeat counting or heartbeat discrimination; (2) Self-report perception of interoceptive accuracy, which is one's beliefs regarding the accuracy of one's interoceptive perception, such as confidence rating (Interoceptive Accuracy Scale) or scores on questionnaires (Interoceptive Confusion Questionnaire); (3) Objective interoceptive attention, which is objective measurement of the degree to which interoceptive signals are the attention object, such as experiencing sampling methods; and (4) self-reported interoceptive attention, which is one's beliefs of the degree to which interoceptive signals are the attention object. Black arrows show that interoceptive awareness can be quantified by comparing one's self-reported beliefs to the objective performance, both accuracy and attention. White arrows show that the relationship across different measurement and performance factors, which are the correspondence between subjective measures of interoceptive attention (the BPQ) and objective measurement of interoceptive accuracy (cardiac interoceptive accuracy tasks). Grey arrows show that a correspondence across measures in the same factor can be quantified. This interoceptive ability model helps researchers to identify the strengths and weaknesses in interoception observed in clinical conditions and isolate individual differences.



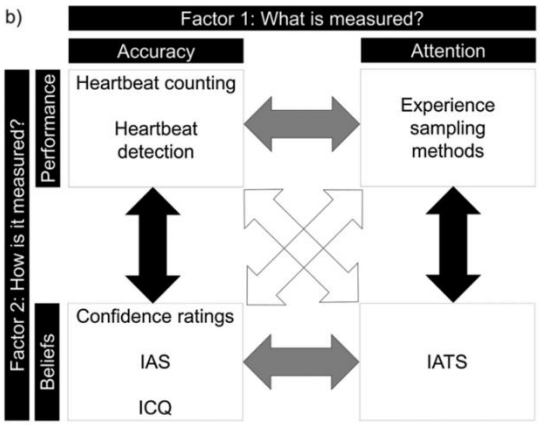


Fig. 2. Model of interoceptive ability. (a) 2×2 factorial model of interoceptive abilities. Factor 1 distinguishes whether accuracy or attention is the target of measurement. Factor 2 distinguishes whether a measure of objective performance or a self-report measure of belief is utilized. For both accuracy and attention, interoceptive awareness can be quantified by comparing one's self-reported beliefs to the objective measure (black arrows). Correspondence across measures within the same measurement factor can be quantified (grey arrows) as well as the relationship across different measurement and performance factors (white arrows). (b) Illustrative tasks that may index distinct facets of the model. *IAS* Interoceptive Accuracy Scale (Murphy et al., 2018). *ICQ* Interoceptive Confusion Questions (Brewer et al., 2016). BPQ Porges Body Perception Questionnaire (Porgs, 1993).

Previous models only distinguish between "how" interoception is measured, such as objective measures of interoception vs. self-report. This 2×2 factorial model also distinguishes between "what' is being measured, such as interoceptive attention vs. accuracy. The discrimination between accuracy and attention reflects the fact that a person reports to be aware of their internal signals but recognize, report that their perception of these signals is inaccurate. For example, they feel hunger even after just have a big lunch. When considering objective measures, a person is able to form a very accurate percept of its internal state when asked to do so, but interoceptive signals are only rarely the object of attention in its everyday life.

C. Independence of Self-reported Interoceptive Accuracy and Attention

It is highly essential to use measures which are sole assessment for interoceptive accuracy or attention in order to assess the independence of self-reported interoceptive accuracy and self-reported interoceptive attention. The Interoceptive Confusion Questionnaire (ICQ) is the only measure, which is available to assess self-perceived trait interoceptive accuracy. The ICQ is a good assessment with convergent validity, but less ideal psychometric properties. Murphy and her collaborators created a new self-report measure of perceived interoceptive accuracy, the Interoceptive Accuracy Scale (IAS) [36]. The IAS is a trait-based assessment measuring global beliefs about one's ability to accurately perceive interoceptive information. In other words, interoceptive domain-general rather than domain-specific. The IAS is used along with the ICQ to test the 2×2 factorial structure of individual differences in interoception. The IAS is constructed to include 21 items of physical sensations, either interoceptive description or association with activation in the insula, a brain specific area associated with processing interoceptive information. The scale asks participants to rate from strongly agree (5) to strongly

disagree (1). Higher scores mean greater self-reported interoceptive accuracy. The IAS was designed to reflect the possibility that an individual may experience difficulties to perceive internal sensations that show differently from the examples given in the ICQ. For example, a person has difficulties to experience hunger, but this may show in overeating rather than forgetting to eat.

Murphy and collaborators designed six experiments (1) to assess the psychometric properties of the IAS, (2) to test the proposed distinction between self-reported accuracy in perceiving and attention to interoceptive information, (3) to measure the association between self-report measures of interoception, both accuracy and attention, and an objective measure of interoceptive accuracy. Results from Study 1 showed that the IAS had good internal consistency, while results from Study 2 demonstrated the test-retest reliability of the IAS was comparable with the other two interoception questionnaire, ICQ and BPQ. Results from Study 2 also revealed that interoceptive accuracy questionnaires, both the IAS and the ICQ, were highly correlated but neither of them was associated with scores on the self-reported interoceptive attention questionnaire, the BPQ. Study 3 showed increasing alexithymia was associated with worse self-report interoceptive accuracy, not with self-report interoceptive attention. Study 5 confirmed the relationship between poor self-report interoceptive accuracy (ICQ and IAS) and alexithymia was independent of depression and anxiety. Study 4 confirmed the correlation between objective performance of interoceptive accuracy and self-report interoceptive accuracy. Study 5 replicated this result from Study 4 and extended that objective measured interoceptive accuracy was only predicated by self-report interoceptive attention (BPQ). Lastly, moment-by-moment judgements of cardiac interoceptive accuracy were predicated by self-report interoceptive accuracy, but not by self-report interoceptive attention.

The results from these six studies suggest that the IAS might be a useful tool to assess the perception of interoceptive accuracy across many interoceptive domains along with the existing measures, the ICQ. No relationship between the self-report measure of interoceptive attention (BPQ) and the self-report measures of accuracy (IAS and ICQ) was observed. Only moderate correlations were observed between the two self-report interoceptive accuracy questionnaires. This set of studies support the fact that there is a distinction between self-reported interoceptive accuracy and self-reported interoceptive attention. The data from these studies also demonstrates the relationship between self-report measures of interoception and mental health, a negative relationship between alexithymia and self-report interoceptive accuracy. It reveals that alexithymia was associated with poor self-report interoceptive accuracy, both ICQ and IAS scores, but not self-report interoceptive attention, BPQ scores. In contrast, self-report interceptive attention only correlated with increasing anxiety.

However, subjective and objective measures for interocetion are differentially related which depend on the specific interoceptive domain to be tested. It is still unclear now whether individual differences in one interoceptive domain, such as respiratory, are linked with individual differences in another domain, such as cardiac. Further across domain research would be useful for assessing self-report measures, such as the IAS and ICQ.

V. Interoceptive Impairment

A. Atypical Interoception

Interoception refers to the sensation and representation of internal physiological signals, from organs such as the heart, stomach, lungs, and skin [2]. Its importance for survival is clear, but it is also viewed as central to the development and organization of higher-level cognition increasingly. For example, interoceptive accuracy, which refers to accurate identification of interoceptive signals, was found to have association with ability of emotion processing, learning and decision making, self-regulation, empathy and theory of mind. These wide range of associations are consistent with theories of embodied cognition that imply cognition is situated in bodily systems, and also spot the role of interoception in both self and other processing.

Evidence suggests that interoceptive abilities have closed relationship to typical functioning, such as emotional processing, learning and decision-making as described in paragraph 2.2 and 2.3, while atypical interoception is associated with impairments in these domains. Importantly, atypical interoception has been observed in numerous clinical conditions, and related to a wealth of transdiagnostic symptoms, such as feeding and eating disorders, anxiety and panic disorders, alcohol and substance abuse, depression [23]. It suggests that atypical interoception may be a general risk factor for the development or maintenance of psychopathology.

Interoception, the perception and interpretation of one's internal bodily states, is highlighted by a number of researchers as the role that atypical interoception may play in a wide range of mental health conditions. It has been proposed that interoceptive atypicalities may represent a common factor for psychopathology. Brewer and her colleagues (2021) argued that interoception played a significant role in typical cognition, particularly within the emotional processing, and in learning and decision making. Their central thesis is that atypical interoception is associated with impairments in numerous functioning domains, and such atypicalities characterize a wide range of psychiatric and neurological conditions.

B. Alexithymia, A Marker of Atypical Interoception

Alexithymia, which was first introduced by Sifneos in 1973, is a sub-clinical condition in which individuals are poor at identifying and describing their emotions, and have an externally-oriented thinking style. The symptoms can result in having troubles in emotional regulation and awareness, as well as deficits in perception of emotional stimuli. Numerous evidence indicates that alexithymia may be the best one to be considered as a failure of interoception.

Murphy and Catmur (2017) demonstrated that alexithymia was associated with interoception across multiple interoceptive domains with multi-dimensional failure in noncardiac domains. They used three experiments to assess the relationship between alexithymia and impaired interoception and suggested that interoceptive ability might

depend variously on the perceived interoceptive signal. As cardiac is supported by many theories as the only one interoceptive domain, as well as the need to assess interoception in noncardiac domains is highlighted, three novel noncardiac interoceptive tasks were implemented, respiratory gauge, muscular efforts and taste sensitivity

A novel measure of interoceptive sensitivity in respiratory domain was introduced in Experiment 1. The result data revealed that individuals with high alexithymia traits relied on exteroceptive signal at judging respiratory output, while those with low alexithymia traits relied on interoceptive signal as exhibited no performance benefit with exteroceptive information. Interoceptive accuracy in two novel domains, muscular effort and taste, were assessed Experiment 2 and Experiment 3 respectively. In each case, increasing alexithymia traits, not autistic traits, were associated with less perceptive accuracy of interoceptive information. Experiment 3 also demonstrated that the association between alexithymia traits and interoceptive accuracy was specific to interoception and confirmed that performance on the exteroceptive control task had no correlation with alexithymia.

These experiments revealed that alexithymia affects multidimension and multidomain of interoception, which was consistent with suggestions that atypical interoception may represent a common factor across psychopathology. The evidence verified that alexithymia might be a marker of atypical interoception, which was associated with both reduced interoceptive accuracy and decreased integration of interoceptive information with ongoing cognition. Even though there were discrepancies between self-reported interoceptive awareness and interoceptive accuracy, self-reported alexithymia was a useful screening tool to identify poor interoception.

C. Interoceptive Impairment and Affective Deficits

Interoception could be defined at many levels and impairment at each conscious level would affect emotion internal states as well as non-emotional ones. Impaired conscious perception of an interoceptive state change has the possibilities to result in reducing attention to internal stimuli and increasing attention to external stimuli [23]. Impaired conscious identification of interoceptive signals could lead to difficulties in discriminating emotional state from other, non-emotional interoceptive states as hunger, and lead to a difficulty in using interoceptive signals to identify between emotional states.

Nearly each aspect of emotion processing depends on interoception. Therefore, all affective impairment conditions are characterized by interoceptive impairment. Major Depressive Disorder is the most closely associated clinical condition with affective deficits. In addition, evidence suggests that affective impairments exist in other emotional difficulties, such as emotion recognition, emotion regulation and empathy have been found in a wide range of conditions, including Autism Spectrum Disorder (ASD), ADHD, Feeding and Eating disorders, Schizophrenia, post-traumatic stress disorder (PTSD), depression and Huntington's disease (Brewer et al., 2021). According to the hypothesis from Brewer and colleagues, affective difficulties shall be interpreted by the presence and severity of co-occurring interoceptive impairment, not the disorder itself. They used a series of studies to examine individuals with a clinical diagnosis with various degrees of alexithymia, which is likely an indicator of interoceptive impairment, and a control group without clinical alexithymia. Impairments, such as reduced empathic response of the insula and impaired identification of emotional facial expression, were observed and thought to be the core characteristics, which were actually due to co-occurring alexithymia, the potential interoceptive impairment. An observation on relationship between alexithymia and stress-related illness showed that it was alexithymia that led to difficulties recognizing which situation was stressful, which led to prolonged exposure, and therefore increased physiological stress response.

Interoceptive accuracy is correlated with social anxiety, emotional lability, emotion regulation, emotional memory, emotional stability, pain perception and the intensity of one's emotional experience. Therefore, it is possible that interoceptive deficits may impact on these impairments whereas these abilities are atypical in clinical population. Better metacognitive interoceptive awareness is also associated with more accurate recognition of others' vocal emotion in autistic individuals. While research on the relationship between interoception and emotional cognition is undergoing, observed evidence does implicate interoception in some of the emotional and social difficulties experienced within clinical population.

D. Interoceptive Impairment and Learning, Reward and Decision-Making Deficits

Learning and decision-making impairment have been observed in ASD, Major Depression, Schizophrenia, Eating Disorders, PTSD, and anxiety. Empirical tests showed the association between interoception and these clinical impairments are scare. Several researchers suggested that interoception is important for drug seeking, withdrawal behaviors, and drug use maintenance, which are treated as a product of atypical learning and decision-making [23]. The recent models show that interoceptive ability controls the extent to which withdrawal-related state of anxiety and panic are perceived, impacts craving. It is found that individuals with high interoceptive ability may be more possible to form associations, or be less able to ignore cravings than those with poor perception of interoceptive information. Individuals with better prediction of interoceptive sensations are better at their craving regulation for unhealthy food.

How the change in addictive behavior results in part from interoceptive change was highlighted. The central point is that the reward value of a stimulus, how pleasurable it is perceived, is a function of the effect it impacts on the body's present internal state. It is suggested that drug addiction results in alternations of the body's present internal state, the representation of the ideal body state. Therefore, the hedonic effects of drugs become less intense, while the craving and withdrawal effects become more intense, which makes drug use change from impulsive to compulsive [37]. This idea is extended by highlighting how interoceptive dysfunction impair detection and recognition of interoceptive signals, and affects emotional awareness, which explains potentially the tendency for some addicts to give up their addiction.

The mechanism underlying the relationship between addiction and interoception is not clear, especially when both

high and low interoceptive abilities are observed. It is possible a quadratic relationship between interoceptive ability and addiction susceptibility. It is possible that low interoceptive accuracy leads to mis-distinguish of substances as more rewarding than it is typical, high interoceptive accuracy and/or attention led to stronger craving sensations. For example, poor interoceptive accuracy implicates in the initial addiction development, high interoceptive accuracy involves in the addiction maintenance. It is also possible that the relationship between addiction and interoception are various depending on which is measured, accuracy or attention.

Studies on the impact of insula lesions provide evidence that interoception underlies craving in addition and learning-related atypicality in other disorders. The insula is the neural basis for craving and reward, which is supported by the imaging studies evidence [38]. Insula activity is associated with craving-relevant stimuli. In contrast, insula and anterior cingulate activation are found to be impaired in individuals with addiction disorders at decision-making and risk-taking.

A few research demonstrated the impact of alexithymia on more explicit learning and decision-making. For example, individuals with alexithymia were found to make risky choices on Iowa gambling task than those who had low alexithymia level, especially when less information of their previous performance was available. Alexithymia appears to be correlated with weaker fear condition indicated by less skin conductance response to situational stimuli, and faster diminish of the response in those who have high, relative to those with media and low level of alexithymia [39].

VI. Outstanding Questions

A. Is Interoception a Unitary Ability?

Whether interoceptive abilities are unitary or whether interoceptive abilities dissociate in a single-dependent way is a crucial question to be answered. In other words, whether an individual with good cardiac sensation has good respiratory, gustatory, pain or temperature sensation remains to be revealed. As interoception is treated as a unitary ability, distinct interoceptive signals are to be processed independently. Multiple signals from multiple domains are integrated to represent the body's internal state as a whole [40]. Findings from the initial studies do not support the hypothesis that interoceptive ability is a unitary construct. However, it is worthy to be noted that the tasks used in these studies are not comparable directly. They vary in their trial and response formats to place different demands on attention and working memory [23]. Future work shall focus on this area, including development of tasks to assess across domains interoceptive abilities to match task demands ideally. Once the suitable measures are ready, there is a possibility to determine the relationship between interoceptive abilities, and whether one domain ability training drives improvements in others.

Since all interoceptive signals cannot be described as a single ability, there may exist several interoceptive clusters, which process a given interoceptive signals associated with some, but not all of other interoceptive signals. Clusters could be classified based on either the fibers carrying different signals or on the neurophysiological pathways that signals follow before reaching the anterior insula [2]. Or clusters could represent psychological relationships, as signals transferring threat information of cardiac and respiratory cues to form a distinct cluster.

There are a range of implications from the hypothesis that interoceptive abilities are unitary. Firstly, it will determine whether interventions for interoceptive impairment can be applied to others. Otherwise, each intervention shall be customized for each individual. Interventions to improve interoception related behaviors shall begin with a whole interoceptive profile for an individual [23]. If some interoceptive abilities belong to one cluster, interventions aiming one ability will improve others within the cluster, and impact symptoms of the relevant disorder.

In addition, the unitary hypothesis will identify whether the findings in one interoceptive domain are applicable to other interoceptive abilities when the conceptual structure of interoception is determined. Cardiac perception is associated with multiple abilities, such as emotion processing, reward and motivation, learning and decision-making [28]. As the relationship among interoceptive domains is not clear, we can not assume that recognition of other interoceptive signals relate to these abilities as well. Understanding the factor structure of interoceptive abilities will help clarifying the definition of interoception, a current controversy in the literature [41]. Some define interoception based on neurophysiological pathways, while others based on the location of a signal's origin. The understanding of the interoceptive signals that belong to a same cluster will lead to a more precise definition, such as the debases over whether proprioception and olfaction shall belong to interoception [2, 3, 42].

Along with the need to consider separable interoceptive domains, determining separable interoceptive dimensions is also necessary, since they may also relate to other abilities and psychopathology differently. Murphy, Catmur and their colleagues proposed that one's objective accuracy in perceiving internal states is different from one's attention towards interoceptive signals, when they aim to do so explicitly [43–45]. The attention towards interoceptive signals may be separable from one's tendency to use or rely on these states to guide daily behavior. If it is the case that these dimensions, accuracy and attention, and the metacognitive awareness are not related to each other strongly, their relationships with psychological disorders are more likely different. For example, individuals with depression, who have typical interoceptive attention, may struggle to perceive interoceptive signals accurately. In contrast, individuals, who have anxiety problems, may pay more attention to internal signals, while autistic individuals may attend to them much less. The interaction or causal relation may exist among these dimensions. For example, reduced attention to internal signals may drive to reduced accuracy, as fewer opportunities to perceive one's internal signals. It is still in early stages for the studies on the relationship between interoceptive attention and accuracy, and metacognitive awareness. Even though some achievement in interoception measurement have been done, as described in Section 3, research still lacks the stability of the relationship between these different dimensions across

different disorders, as well as the relationship between these dimensions and disorder symptoms.

The hypothesis that interoception is a unitary ability also links with alexithymia. Primarily, alexithymia is seen as a reflection of cognitive impairment in representing and labeling of emotions. At present, it is also argued that alexithymia plays the central role of affective difficulties, which is characterized by decreased ability in experiencing emotions. Based on affective and cognitive domains, alexithymia is categorized into three types. Type I alexithymia is used for individuals who experience impairment in both, while Type II alexithymia refers to those with impairment only in the cognitive domain [46]. Type III alexithymia is the most recent one which is identified with affective, but not cognitive impairment [47]. It is unsurprised that impairment in the affective and cognitive domains is associated with different neural atypicality. Both dimensions are more likely to link with interoceptive abilities.

Interoception may also be separated at the perceptual level from the cognitive level, which involves representing, recognizing and verbal labelling the internal states. Evidence has been found for a distinction between interoceptive perception and interoceptive cognition (Brewer et al., 2021). For example, patients were observed to struggle to label smells even though they were able to discriminate perceptually between smells. Another example, patients, who had insula lesions, were observed to be able to perceive pain, but could not categorize those signals as painful. The need to distinguish between perception and recognition of internal states will be highly appreciated.

The last element relevant to the unitary ability hypothesis is the developmental origins of interoceptive impairment. Although alexithymia research shows that there exists developmental and acquired routes, very few studies focus on this in the non-emotional interoception domain [48]. It is important to know whether interoceptive impairment are different in their nature, which depends on whether they are neurodevelopmental, either develop in response to environmental triggers or develop in response to brain injury. Also, it is to be investigated whether interoceptive impairment is a stable trait or a dynamic state. Relevant debate on alexithymia, a state or trait phenomenon, also exists. While some argue that severity vary, especially with disorder symptoms, stability shows to differ with severity of alexithymia. The assessment and comparison of developmental and stability of interoceptive abilities, across multi-domains and multi-dimension of interoception, will help determine the hypothesis of unitary construct of interoception and confirm that it is not a fractionated construct [23].

B. How Can Interoceptive Abilities be Improved?

Since poor interoception contributes to multiple symptoms and impairment in numerous cognition aspects, it is obvious to improve those interoceptive abilities which are deficient. As many ways have been showed the functions to improve interoception, there is a need to determine whether the improvements are long-lasting, generalized across domains, and really helpful to reduce psychopathology [49]. As soon as the nature of relationship among interoception, cognition, psychopathology is clarified, the most efficient and effective interventions could be determined.

So far, heartbeat perception training is the way commonly used to improve interoception, which leads to improved perception of an individual's heartbeats. However, whether the cardiac domain training can improve interoceptive abilities in other interoceptive domains is still to be determined, such as perception and recognition of signals representing respiration, hunger, temperature, pain.

In addition, meditation is assumed as a way to improve interoception. Meditation experience is claimed to be associated with increased volume of the insula and ACC [50, 51]. Functional activation of these interoceptive region is found during meditation operation. Experienced meditators showed increased coherence levels between subjective and objective measure of emotional arousal [52]. Improved respiratory perception was also observed in meditators, which is possibly due to the reason that meditation is focuses on breath, respiratory and cardiac signals. However, recent meta-analysis did not find evidence to show correlation between meditation and interoceptive accuracy, while only the cardiac domain was investigated [53].

The distinction between interoceptive accuracy and attention is related to the relationship between interoception and meditation as well as other interoceptive training forms. Body-focus is the nature of meditation that makes the practice to increase interoceptive attention and encourage meditators to use internal cues. In turn, increased interoceptive attention may lead to increased interoceptive accuracy [54,55]. Evidence shows that meditation has been found to increase self-reported interoceptive attention, confidence and easy perception of completion of heartbeat discrimination task. It is significant to use measures to distinguish between interoception dimensions, to enable tailor-made interventions to be more effective for individuals' interoceptive impairment [23]. Critically, whether interventions change individuals' attention to accuracy perceiving, internal cues may affect differently in various clinical populations.

A review, based on studies reporting psychological interventions' effect on alexithymia, showed that reductions in alexithymia are quite common, especially with alexithymia specific targeted interventions [56]. The causes of reductions, either interoceptive accuracy or attention, is still under investigation. As alexithymia is relevant to emotional states, improving general interoceptive abilities, may reduce alexithymia [23]. However, alexithymia specific targeted inventions are not sufficient to improve interoceptive skills. If the hypothesis is true, interoceptive domain training may be an effective way to improve recognition of internal states, both emotional and non-emotional. It is worth to note that not all individuals or disorder groups could benefit from interoceptive training, even though future research should aim to determine how interoceptive abilities across domains and dimensions could be improved.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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