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MODALITIES AND DIMENSIONS OF INTEROCEPTION

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List of publications that the dissertation is based upon[1]

<u>Ferentzi, E.,</u> & Köteles, F. (2016). A szívdobogás percepciójának kapcsolata különböző patológiákkal [The relationship of heartbeat perception with different pathologies]. In S. Csibi & M. Csibi (Eds.), *Aktuális kérdések és alkalmazások az orvosi pszichológia területéről [Current topics and methods in medical psychology]* (pp. 145–162). Kolozsvár: Ábel Kiadó.

<u>Ferentzi, E.,</u> Köteles, F., Csala, B., Drew, R., Tihanyi, B. T., Pulay-Kottlár, G., & Doering, B. K. (2017). What makes sense in our body? Personality and sensory correlates of body awareness and somatosensory amplification. *Personality and Individual Differences*, *104*, 75–81.

<u>Ferentzi, E.,</u> Drew, R., Tihanyi, B. T., & Köteles, F. (2018). Interoceptive accuracy and body awareness – Temporal and longitudinal associations in a non-clinical sample. *Physiology & Behavior*, *184*(Supplement C), 100–107.

<u>Ferentzi, E.,</u> Bogdány, T., Szabolcs, Z., Csala, B., Horváth, Á., & Köteles, F. (2018). Multichannel investigation of interoception: Sensitivity is not a generalizable feature. *Frontiers in Human Neuroscience*, *12*.

<u>Ferentzi, E.,</u> Tihanyi, B. T., Szemerszky, R., Dömötör, Z., György, B., & Ferenc, K. (2018). Interocepció. Narratív összefoglaló [Interoception. Narrative review]. *Mentálhigiéné És Pszichoszomatika*, *19*(4), 297–334.

Pollatos, O., & <u>Ferentzi, E.</u> (2018). Embodiment of Emotion Regulation. In G. Hauke & A. Kritikos (Eds.), *Embodiment in Psychotherapy: A Practitioner's Guide* (pp. 43–55). Cham: Springer International Publishing.

<u>Ferentzi, E.,</u> Horváth, Á., & Köteles, F. (2019). Do body-related sensations make feel us better? Subjective well-being is associated only with the subjective aspect of interoception. *Psychophysiology*, *56*(4), e13319

1 Note: Each co-author has granted permission for the given publication to be included in the current dissertation.

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This dissertation is based upon four already published studies. I would like to thank everybody who contributed in the whole process of making these papers: from planning through data collection till writing the very last version of the manuscript. Accordingly, I would like to thank to all the participants of the studies, my co-authors, and the whole research team (including past members) of the Ádám György Psychophysiology Lab for their contribution, especially to György Bárdos, Tamás Bogdány, Barbara Csala, Zsuzsanna Dömötör, Raechel Drew, Áron Horváth, János Körmendi, Zsuzsanna Szabolcs, Renáta Szemerszky, and Benedek Tihanyi.

I spent eleven months in Germany in 2018-2019 with a scholarship provided by the Deutscher Akademischer Austausch Dienst (DAAD). The empirical studies completed during my DAAD research scholarship on interoception are not part of my doctoral dissertation, but the scientific discussions through my stay in Germany influenced very much my thinking about the topic. I would like to thank for the discussions with Olga Pollatos and Oliver Wilhelm and their research groups at Ulm Universität, and also with Laura Kaltwasser and Werner Sommer at Humboldt-Universität zu Berlin.

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Foreword

Although the term ‘interoception’ is not commonly used in the everyday language, and not even in the medical practice, the phenomenon it refers to is one of the most basic human experiences (Ceunen, Vlaeyen, & Van Diest, 2016). The perception of the internal bodily signals is significant in various contexts, such as symptom perception (Van den Bergh, Zacharioudakis, & Petersen, 2018), decision making (Dunn, Galton, et al., 2010), situations evoking empathy (Grynberg & Pollatos, 2015), or emotions (Pollatos, Herbert, Matthias, & Schandry, 2007; Wiens, Mezzacappa, & Katkin, 2000). Individual differences of interoception seems to relate to healthy psychological functioning (N. A. Farb & Logie, 2018; N. A. S. Farb et al., 2015; Khalsa et al., 2018; Manos Tsakiris & Critchley, 2016), and the emergence of a number of psychopathologies (Duquette, 2017; Murphy, Brewer, Catmur, & Bird, 2017).

The notion that the perception of the internal bodily signals has a significant role in the everyday functioning, dates back to the very beginning of the history of scientific psychology (James, 1884; Lange, 1885). More recent theoretical accounts also support this view (Craig, 2010; Damasio, 1994, 1999, 2010; S Epstein, 2003; Rogers, 1951). Recently, a complex hierarchical, neuro-cognitive framework of the conscious and unconscious regulation of emotional states has been developed, which attaches great importance to interoception (R. Smith & Lane, 2015). The growing popularity of interoception research is also reflected by a thematic issue of the prestigious *Philosophical Transactions of the Royal Society B: Biological Sciences* from November 2016, which covered the main topics of the current empirical studies. Very recently, the current scientific knowledge on various aspects of the phenomenon was summarized in an edited book (Manos Tsakiris & De Preester, 2018) published by the Oxford University Press.

Considering the acknowledged significance and growing popularity of the field, it is extremely important to define interoception precisely. Without an appropriate understanding of the construct itself, empirical results cannot be interpreted correctly. This leads us to the topic of interoceptive modalities and dimensions, which represents the major topic of this doctoral thesis.

The structure of my dissertation is the following. At very beginning of the

Introduction, I will provide the reader with a number of possible definitions of interoception. Afterwards, I will introduce various interoceptive modalities (i.e. internal sensory channels), and also list several factors that might influence the assessment of interoceptive accuracy, and therefore bias the results. Following that, multichannel investigations will be introduced briefly. After discussing the modalities of interoceptive accuracy, I will introduce another important dimension of interception, namely interoceptive sensibility, measured with self-rating. Firstly, I will list several related questionnaires; and secondly, provide an overview about the relation of the two main interoceptive dimensions, accuracy and sensitivity. Following that, I will discuss the relation of interoception and health, namely what might be the advantages and disadvantages of a certain level interoception. I will also present an information processing model called predictive coding, that might be able to explain some significant features of the interoceptive processes. Last but least, I will present the aims of my doctoral dissertation.

Following the Introduction, I will introduce the four empirical studies my thesis based upon. Study 1 (Chapter 2, Ferentzi, Drew, Tihanyi, & Köteles, 2018) investigates the longitudinal associations between two interoceptive dimensions, namely interoceptive accuracy (assessed with the heartbeat perception task of Schandry, Schandry, 1981) and sensibility (assessed with the Body Awareness Questionnaire, Köteles, 2014; Shields et al., 1989). Both constructs showed good test-retest reliability ($r = 0.60$ and $r = 0.73$, respectively; $p < 0.001$ in both cases). They were not associated at baseline, and also did not predict each other over an eight weeks time period.

Study 2 (Ch.3, Ferentzi et al., 2017) focuses on four interoceptive modalities, namely on heartbeat perception, balancing ability, and the perception of pain and bitterness. This paper also included self-report variables such as interoceptive sensibility, somatosensory amplification and the Big Five personality factors. The sensory measures of interoception were not associated. Somatosensory amplification associated with emotional lability and introversion of the Big Five personality factors, and also with the perception of pain and bitter taste. Interoceptive sensibility was associated with openness and conscientiousness of the Big Five personality factors, but was not related to any of the sensory measures of interoception.

Study 3 (Ch.4, Ferentzi, Bogdány, et al., 2018) also focuses on the interoceptive modalities on an independent sample, and includes two additional sensory modalities, namely gastric sensitivity (assessed with the water load test) and two tasks measuring the proprioceptive sensitivity of the elbow joint. The correlation analysis showed significant association only between modalities belonging to the same sensory channel (i.e. level of pain threshold and tolerance, bitter intensity and unpleasantness, gastric fullness and unpleasantness). Similarly, the three factors the emerged in the two types of factor analyses represented the three aforementioned channels.

Finally, Study 4 (Ch.5, Ferentzi, Horváth, & Köteles, 2019) investigates the association between heartbeat perception, gastric sensitivity, proprioceptive sensitivity and subjective well-being. Subjective well-being associated only with the self-reported aspect of interoception (i.e. interoceptive sensibility), but not with the sensory measures of interoceptive accuracy.

The Discussion of my PhD dissertation will start with a brief summary of the findings of the four introduced empirical studies. Following this, I will write about the independence of the assessed dimensions and modalities of interoception. This chapters are followed by the introduction of some additional theories as possible models of interoceptive information processing, with a focus in emotional processes. These frameworks might also help to understand better the relation of interoception to emotion, emotion regulation, and mental health. The Discussion will continue with a brief summary of the limitations of the four presented papers, followed by some suggestions for future studies. The dissertation will end with a brief conclusion.

1. Introduction[2]

1.1. Definition

Interoception has been defined in different ways (Ceunen et al., 2016). According to our knowledge, the origin of the term itself was applied for the first time by Sherrington in adjective form ('interoceptive') and as 'interoceptor' (Sherrington, 1906), and he used the term to sensory receptors for stimuli originating inside the body (Cameron, 2001). In a scientific context, the term 'interoception' was used first in the 1940th (Freeman & Sharp, 1941). The phenomenon itself was described with several different terms during the past century, such as 'somesthesis' and 'coenesthesis' (Ceunen et al., 2016).

Recently, interoception has been defined in the Preface of a recently published thematic book as "the body-brain axis of signals originating from the internal body" (Manos Tsakiris & De Preester, 2018, p. v). Most of the definitions of interoception are in accordance with this description, the main difference is how 'internal' is defined exactly.

Originally, Sherrington defined interoception as opposed to exteroception, and consequently, the skin as a demarcation line had great significance (Sherrington, 1906). He used 'interoceptive' as a synonym for 'visceroceptive', i.e. signals originating in visceral organs (i.e. organs of the digestive, respiratory, cardiovascular and urinary-reproductive systems) (Ádám, 1998). Additionally, Sherrington also distinguished interoception from proprioception, the perception of the position and movement of the body based on information originating from the muscles, joints and tendons. According to his view, the sensation of temperature and pain, for example, were not interoceptive processes (Sherrington, 1906).

Although some scholars still highlight visceroception among the interoceptive

2 The Introduction contains translated and edited parts of the following papers:
Ferentzi, E., & Köteles, F. (2016). A szívdobogás percepciójának kapcsolata különböző patológiákkal [The relationship of heartbeat perception with different pathologies]. In S. Csibi & M. Csibi (Eds.), *Aktuális kérdések és alkalmazások az orvosi pszichológia területéről [Current topics and methods in medical psychology]* (pp. 145–162). Kolozsvár: Ábel Kiadó;
Ferentzi, E., Tihanyi, B. T., Szemerszky, R., Dömötör, Z., György, B., & Ferenc, K. (2018). Interocepció. Narratív összefoglaló [Interoception. Narrative review]. *Mentálhigiéné És Pszichoszomatika*, *19*(4), 297–334. https://doi.org/10.1556/0406.19.2018.014

modalities, implying a narrow definition (Cameron, 2002); the majority of the current definitions are more inclusive (Ceunen et al., 2016; Craig, 2002, 2015; Ehlers & Breuer, 1992; Yoris et al., 2015). These broader approaches include various different sensations, such as “temperature, pain, itch, tickle, sensual touch, muscular and visceral sensations, vasomotor flush, hunger, thirst, air hunger"; or, in general, any “sensations related to the body’s state” (Craig, 2002, p.697). There is no complete agreement, however, on the exact definition on interoception. There are scholars who do not regard prorioception as part of interoception (Mehling et al., 2009), while others define interoception as the combination of proprioception and visceroception (Vaitl, 1996).

While interoception is defined as a conscious perception by most of the authors (if not explicitly, indirectly by the operationalization of the empirical studies), some scholars argue, that interoception does not have to be necessarily conscious (Cameron, 2002). According to Cameron, if we accept this broader definition (as there are plenty of situations when we are not aware of the internal signals themselves), we are more consistent with the hypothesis that visceral sensory impulses are significant factors in the control of behavior (Cameron, 2002).

It is important to mention that (1) the central nervous system receives and processes information of various organs and functions from exteroceptive and interoceptive sources simultaneously (e.g. heartbeats trigger the baroreceptors of the aorta, the mechanoreceptors of the skin and also generate auditory sensations) (Ádám, 1998; F de Vignemont, 2018); and (2) exteroceptive, interoceptive, and proprioceptive information becomes more and more integrated on higher levels of processing (aka multisensory or intermodal integration) (Blanke, Slater, & Serino, 2015; Khalsa et al., 2018). Finally, humoral information seems also to contribute to the internal representation of the body (Aziz & Ruffle, 2018; Colombetti & Harrison, 2018; Damasio, 2003; De Preester, 2018).

These different internal sensations are also described as the modalities or channels of interoception (Ferentzi, Bogdány, et al., 2018). In this thesis, I will use the terms ‘modalities’ and ‘(sensory) channels’ interchangeably. I have to point out, however, that this terminology might be misleading, as these terms do not necessarily or clearly refer to distinct receptors and neural pathways.

In the following, I will introduce two dimensions of interoception: interoceptive accuracy (as assessed with behavioral/sensory measures; see Ch.1.2) and interoceptive sensibility (as assessed with self-rated questionnaires; see Ch.1.3) (Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). I will start with interoceptive accuracy, and its modalities or channels.

1.2. Interoceptive accuracy

Interoceptive accuracy is a multimodal construct, meaning that it can be investigated with with various interoceptive channels or modalities.

Possible channels to investigate

As we saw above, even the narrowest definition of interoception includes the visceral channels. Among these, the investigation of the cardiovascular system, especially the assessment of heartbeat perception, is the most widespread. The two main approaches to assess heartbeat perception are the tracking paradigm (Davidson, Horowitz, Schwartz, & Goodman, 1981; McFarland, 1975; Schandry, 1981) and the discrimination paradigm (Edward S. Katkin, Blascovich, & Goldband, 1981; Whitehead, Drescher, Heiman, & Blackwell, 1977). These two techniques will be discussed later in details. In the cardiovascular system, other sensations have been also investigated, such as heart rate and blood pressure (Greenstadt, Shapiro, & Whitehead, 1986; Pennebaker & Watson, 1988).

In the respiratory system, air hunger (Liotti et al., 2001), respiration with airway resistance (Daubenmier, Sze, Kerr, Kemeny, & Mehling, 2013; Giardino et al., 2010; Zechman & Davenport, 1978) have been investigated.

To investigate the gastrointestinal system, both invasive and non-invasive techniques are known. Concerning gastric sensitivity, there are several versions of the so called water load test (Boeckxstaens, Hirsch, Berkhout, & Tytgat, 1999; Boeckxstaens, Hirsch, Van Den Elzen, Heisterkamp, & Tytgat, 2001; Chen, Lin, Chen, & Huang, 2005; M. P. Jones, Hoffman, Shah, Patel, & Ebert, 2003; van Dyck, 2015), a popular non-invasive task during which the participants have to drink a certain amount of water in a fixed time-period. In some variations the water also contains nutrients (Mimidis, 2007). Various drinking tests are also used in clinical practice, for example in the case of functional dyspepsia (Chen et al., 2005; Mimidis, 2007). Invasive techniques (e.g. balloon distension) are appropriate to assess the sensitivity to induced tension of various parts of the gastrointestinal tract (e.g. esophagus, stomach, large intestine, rectum) in a highly accurate way (Ádám, 1998; Hölzl, Erasmus, & Möltner, 1996).

Interoception measurements were also performed to assess sexual dysfunctions. For example, a study investigating female participants compared the physiological changes following the visual sexual stimulus with the reaction time required to respond; the later was interpreted as a measure of interoception (Silverstein, Brown, Roth, & Britton, 2011). Another study compared the level of the subjective and objective arousal with the assessment of vaginal pulse amplitude (Brotto & Yule, 2010).

Interestingly, there are acknowledged authors (Vaitl, 1996) who consider the investigation of the endocrine system as a field interoception research.

There are several tasks designed to assess the sensitivity of the skin. The Quantitative Sensory Testing (Schunke et al., 2016) is a complex neurological test battery that contains 13 different types of sensory stimuli. Among others, the sensation threshold and tolerance level of cold and hot, and mechanically induced stimuli is investigated, along with the detection of temperature change, and paradox temperature sensation. The Somatic Signal Detection Task (Lloyd, Mason, Brown, & Poliakoff, 2008; Mirams, Poliakoff, Brown, & Lloyd, 2012) uses only the stimulation of the skin, and assess the accuracy of the sensation of near-streshold stimuli. There are also examples of studies investigating the accuracy of perception of the skin conductance (sweat) (Steptoe & Noll, 1997), and the temperature change of the skin surface (Pennebaker, 1982).

The methods to assess pain sensitivity (more precisely: pain threshold and pain tolerance) apply various stimuli to induce pain, such as cold (Siedlecka, Klimza, Łukowska, & Wierzchoń, 2014), heat (Hegedüs et al., 2014), electric current (Siedlecka, Spychała, Łukowska, Wiercioch, & Wierzchoń, 2018), pressure (Pollatos, Füstös, & Critchley, 2012), or hypoxia of certain muscles (Amanzio & Benedetti, 1999).

A review about assessments investigating proprioceptive accuracy of the joints described three main types of the tasks: threshold to detection of passive motion, joint position reproduction, and active movement extent discrimination (Han, Waddington, Adams, Anson, & Liu, 2016). Methods assessing muscle tension are using the weight discrimination task (Chang & Lenzenweger, 2005). There are also measurements to investigate balancing ability (Berg, 1989).

Although interoception, especially in theoretical context, is often mentioned without any further specification, it was suspected relatively early (Carroll, 1977; Pennebaker & Hoover, 1984) that there might be no association between the results using different methods or investigating different channels. Findings of two studies presented in this thesis strongly supports the idea of the independency of sensory modalities with respect to perceptual accuracy (Ferentzi, Bogdány, et al., 2018; Ferentzi et al., 2017). In the following I will list the major issues of the assessment of interoceptive accuracy.

Factors influencing the assessment of interoceptive accuracy

The most widely used (and also widely criticized) paradigms to assess interoceptive accuracy are the two types of the heartbeat perception task, i.e. the tracking task (often linked to Schandry, 1981; although some versions have been used before his article, see: McFarland, 1975) and the discrimination task (Brener & Kluvitse, 1988), also called heartbeat detection task (Ring & Brener, 2018). In the following, I am going to demonstrate the difficulty to measure interoceptive accuracy by introducing these two techniques in more details.

During the tracking task, the participant has to follow his or her own heartbeats with silent counting or finger tapping, and to provide a number by the end of each trial (Schandry, 1981). Normally there is a short training interval, followed by three to four trials with varying length (between 15 and 100 seconds) (Fischer, Messner, & Pollatos, 2017). Participants are asked to count their heartbeats without and checking their pulse manually or applying any techniques to help better heartbeat perception, such as stop breathing. Actual heartbeats can be recorded with various techniques, such as the usage of a fingertip pulse oximeter, a chest strap with polar watch or ECG electrodes. For each trial, the following formula is calculated: 1−|(recorded heartbeats−counted heartbeats)/recorded heartbeats|. The average of the trials provides the score of heartbeat perception accuracy, between 0 and 1. Higher value indicates higher accuracy level (i.e. smaller deviations from the actual number of heartbeats).

During the discrimination task, the participants have to decide, whether short (e.g. 10 sec – Whitehead, Drescher, Heiman, & Blackwell, 1977, 15 sec – Weisz, Balázs, & Ádám, 1988) series of visual, auditory, or tactile stimuli are in accordance with his or her heartbeats (E.S. Katkin, Reed, & Deroo, 1983; Whitehead et al., 1977), and have to decide in a yes-or-no manner if the rhythm was identical or not. To rule out temporal effects, timing of presentation of the stimuli was manipulated in several studies; for example, they were administered 0, 100, 200, 300, 400, or 500 ms following each R-wave (i.e. peak of the ECG signal that initiates ventricular systole) (Brener & Kluvitse, 1988). At the group level, stimuli 200-300 ms after R-wave are judged most contiguous with the heartbeats (Brener & Kluvitse, 1988). An early study that investigated the Whitehead-type discrimination task (which provides only two types of stimuli set) found that most participants can well discriminate stimuli in the first quarter second of the cardiac cycle from later occurring events (Clemens, 1984). A more recent study found that a minimum number of 40 trials is needed for a reliable heartbeat discrimination measurement (Kleckner, Wormwood, Simmons, Barrett, & Quigley, 2015).

The notion that the tracking and the discrimination tasks might measure something different is not a recent discovery (Carroll, 1977; Pennebaker & Hoover, 1984), and has been confirmed by more recent studies, as we will see in the following.

A study (Knoll & Hodapp, 1992) found that only the very good and very poor heartbeat perceivers performed similarly on the tracking task (Schandry, 1981) and a version of the discrimination task (Whitehead et al., 1977).

The cold pressor test affected differently the performance on the two paradigms, implying that the two task requires different abilities. While interoceptive accuracy increased when it was measured with tracking task, it decreased in the case of the discrimination task (Schulz, Lass-Hennemann, Sütterlin, Schächinger, & Vögele, 2013).

Although most of the studies do not show direct relation between the different tasks of heartbeat perceptions (Garfinkel, Seth, et al., 2015), there are some findings that contradict to these results, by discovering weak correlation (Hart, McGowan, Minati, & Critchley, 2013).

The validity of the discrimination task (using external stimuli) is problematic mainly because during the test the participant has to compare internal stimulation with external (Pennebaker, 1982). This is hard to consider as a pure task of interoception, and therefore, its ecological validity is rather low. The main criticism of the tracking task is, on the other hand, that heartbeat counting is very much influenced by the knowledge or the belief of the participant (Ring & Brener, 1996; Ring, Brener, Knapp, & Mailloux, 2015). Furthermore, both techniques share the problem that they require divided attention (although not the same way), a cognitive skill with great individual differences. There are also another factors that might help the participants to reach higher scores. In the case of the discrimination task, for example, 24.3% of the variance of the precision of heartbeat detection can be explained by the subject's ability to judge the simultaneity of lights and tones; furthermore, mechanical sensitivity accounted for an additional 8.5% (Knapp, Ring, & Brener, 1997). My own research experience with the mental tracking paradigm of Schandry (Schandry, 1981) shows that the exact device used to assess the actual heartbeats is a significant factor. Pressure posed by the fingertip pulse oximeter on the skin very often causes extra sensations which makes the identification of the heartbeats rhythm easier (and therefore this device has been used only once in published studies of the Ádám György Psychophysiology Lab, but not in the papers introduced by this dissertation). This evoked sensation appears rarely with the chest strap (only if it is too tight), and never with the ECG electrodes.

The exact instruction of the tracking task might be also a significant influencing factor. When stricter instruction is applied, i.e. the participant is asked to count only the sensations that are definitely heartbeats, people tend to count less as compared to the instruction of counting all sensations that are thought to be heartbeats (Hart et al., 2013). According to my own experience in different laboratories that apply the mental tracking paradigm, there are substantial differences among the details of the instruction used ("please count slight sensations, but do not guess'; "if you don't feel anything, you can report zero" versus the instruction encouraging guessing if the participant does not feel anything). In the later case, hardly anybody ever report zero heartbeats.

Recently, attempts have been made to solve or at least minimize some of the above mentioned methodological problems (Sedeño et al., 2014; Yoris et al., 2015), but none of the new techniques provides a perfect solution.

Regarding the influencing factors, there is no consensus on gender differences either. According to some empirical studies, men perceive their heartbeats more accurately (Grabauskaitė, Baranauskas, & Griškova-Bulanova, 2017; Edward S. Katkin, 1985; Vaitl, 1996), however this finding was not confirmed by some other scholars (Khalsa, Rudrauf, & Tranel, 2009; Pennebaker, 1982). According to some speculations, the differences in systolic blood pressure between males and females might explain a proportion of the gender differences (Pennebaker & Hoover, 1984), which might influence the strength of the pulse (O'Brien, Reid, & Jones, 1998). Additionally, early empirical results show that those with lower body fat percentage performed better at heartbeat perception task (as tactile sensations are decreased by body fat) (G. E. Jones, Jones, Rouse, Scott, & Caldwell, 1987; Montgomery & Jones, 1984), and later findings confirmed that gender differences might be well explained by the higher body fat percentages of females (G. E. Jones, Rouse, & Jones, 1988). According to another argument (Pennebaker & Roberts, 1992), males generally use more internal cues, while females rely more on environmental ones. Consequently, males might be better at sensory task under laboratory circumstances, but the gender difference is not substantial in everyday situations.

Age might be also an influencing factor. A longitudinal study investigating a large sample of children (n = 1675, 6-11 years old) found low interoceptive stability a year later (A. Koch & Pollatos, 2014); this finding suggests that under a certain age, interoceptive abilities might be not stable characteristics, and the specific factors that might be in the background of this phenomenon is still to discover. According to cross-sectional study assessing adults between 22 and 63 years, the level of interoceptive accuracy decreases with age (Khalsa, Rudrauf, & Tranel, 2009).

As we can see, there are several factors that might influence the performance on both types of heartbeat perception tasks. Besides this, there is a basic problem with the assessment of interoceptive accuracy. It is very hard to control or to measure the strength of the signals originating within the body. This makes the exact judgment of the individual performance impossible. As we saw above there are some interoceptive modalities, where external stimulation is possible (e.g. pain stimulation, proprioceptive tasks), but this is not possible with all the interoceptive channels. A great advantage of the heartbeat perception tasks are, that the physical signal itself (i.e. the heartbeat) is easy to capture (e.g. with ECG); however, the exact strength of the internal signal itself, just like the individual response patterns show great variance. Signal detection theory is an excellent tool to control the later (Green & Swets, 1966), which is an important argument for using the discrimination task.

Interestingly, the investigation of the influence of general cognitive ability on interoception – especially that of attention, e.g. shared and sustained – is not a widely investigated topic. This might be, however, a significant factor, as only the focus on the body parts itself can cause changes in the sensation (Tihanyi, Ferentzi, Beissner, & Köteles, 2018). Paradigms of interoceptive accuracy assume that participants have to be attentive, but it is hardy ever controlled.

Investigation of multiple channels

Most of the studies show that the perceptual accuracy of different modalities show no or only weak to moderate associations. For example two studies found no relation between heartbeat perception and respiratory resistance (Garfinkel et al., 2016; Harver, Katkin, & Bloch, 1993); while a third one found moderate association ($r = 0.36$, $p < 0.05$) between heartbeat perception and respiratory resistance, just like between skin conductance level accuracy and respiratory level accuracy ($r = 0.36$, $p < 0.05$). No association was found between the accuracy of heartbeat perception and sweat gland activity perception (Steptoe & Noll, 1997). A study assessing the sensitivity to heat pain and heartbeat perception found no relation between pain experience and the level of heartbeat perception scores (Werner, Duschek, Mattern, & Schandry, 2009). Last but not least, two studies using slightly different methodologies found moderate associations between heartbeat perception and gastric sensitivity (Herbert, Muth, Pollatos, & Herbert, 2012; Whitehead & Drescher, 1980). More details of these studies will be provided below (see: the Introduction of Study 3, Ch.4).

Interoception can be measured not only by sensory tasks, but by questionnaires too. From the very beginning of the scientific research of interoception, self-rated questionnaires have been widely used to assess interoception (Carroll, 1977). In the following, I will focus on this dimension (which is also called interoceptive sensibility) of interoception.

1.3. Interoceptive sensibility

Before the introduction of the most commonly applied questionnaires of interoceptive sensibility, there are some general topics to discuss regarding the self-rated assessment of interoception.

The terms themselves, interocepive sensibility or awareness are relatively new (Ceunen, Van Diest, & Vlaeyen, 2013; Garfinkel & Critchley, 2013). The investigation of the phenomenon with questionnaires, however, started decades before 2013. Measures developed earlier use different terminology, such as (private) body consciousness (Miller, Murphy, & Buss, 1981), body awareness (Shields et al., 1989), body responsiveness (Daubenmier, 2005), or somatic absorption (Köteles, Simor, & Tolnai, 2012); with some exception, for example the Interoceptive Awareness Subscale of the Eating Disorder Inventory (Garner, Olmstead, & Polivy, 1983). It is another question whether this questionnaires are the measures of interoception or not (Mehling et al., 2009, 2012).

The major distinction that can be made between the questionnaires measuring the perception of the internal cues, based on the type of the bodily signals, and their interpretation. Some assessments involve items with negative emotional valence or symptom perception (Barsky, Goodson, Lane, & Cleary, 1988; Main, 1983; Mandler, Mandler, & Uviller, 1958; Stern & Higgins, 1969), while others focus on pure bodily signs (Shields et al., 1989). The later approach is more recent, and the construct itself was originally called ‘body awareness’ (Mehling et al., 2009; Shields et al., 1989). It is an ongoing debate, whether the modern term of ‘interoceptive sensibility’ is synonymous with ‘body awareness’ or not. Some of the reviewers of our papers argued that it is not, because body awareness is broader and includes external modalities (Ferentzi, Drew, et al., 2018; Ferentzi et al., 2017). A review about 'body awareness', however, says that it is "the perception of bodily states, processes and actions that is presumed to originate from sensory proprioceptive and interoceptive afferents and that an individual has the capacity to be aware of” (Mehling et al., 2009, p. 4), which covers perfectly the construct of interoceptive sensibility. I will write more about the terminology of interoception, and also about the distinction between body awareness and interoceptive sensibility below (see Chapter 1.4).

Questionnaires

One of the first questionnaires in the literature of interoception is the Autonomic Perception Questionnaire (APQ) (Mandler et al., 1958). The APQ focuses on the following seven physical sensations: heart rate, sweating, changes in body temperature, breathing, stomach upset, muscle tension, and blood pressure. The questionnaire was widely used among scholars investigating biofeedback, and along with this, the capacity to control and perceive bodily signals (Carroll, 1977). A study using APQ was one of the first that suspected that interoceptive accuracy and sensibility might not relate (McFarland, 1975). Worth to note, however, that the APQ assessed the physical sensations of affective states.

Seymour Fisher was a distinguished scholar of body focus who published three books on the topic (Fisher, 1970, 1974; Fisher & Cleveland, 1968), and developed various methods to investigate the topic. An interesting approach among these was, when he asked the participants to write 20 statements, listing what are they aware of at the moment; the level of body focus was assessed with the number of items related to bodily sensations (Fisher, 1974).

Miller and colleagues, unlike Fisher, wanted to separate the private aspect of the body from the public one. The Body Consciousness Questionnaire was developed in 1981 with three subscales: Private Body Consciousness, Public Body Consciousness, and Body Competence (Miller et al., 1981).

The Somatosensory Amplification Scale (Barsky et al., 1988; Barsky & Wyshak, 1989, 1990) measures somatosensory amplification, a construct that was described as the tendency to experience somatic sensation as intense, noxious, and disturbing (Barsky et al., 1988). In Study 2 of this dissertation (Ch3, Ferentzi et al., 2017), somatosensory amplification is one of the assessed variables. The relation of the construct to the measures of interoception is discussed there in details (see Chapter 3.1 and 3.4). Therefore, to avoid redundancy, this topic will not be discussed here.

The Body Perception Questionnaire of Porges (Porges, 1993) has five subscales, i.e. awareness, stress response, autonomic nervous system reactivity, stress style, and health history inventory. As we can see, not all of subscales are closely related to interception, the later ones are not mentioned among the measures of interoception (Mehling et al., 2009). A recent study investigated the two subscales (body awareness and autonomic nervous system reactivity) of the Body Perception Questionnaire-Short Form on a large multicultural sample (Cabrera et al., 2018). Body awareness was described as a single factor, but interestingly, items investigating the autonomic nervous system reactivity constructed two factors, one for organs above and one for organs below the diaphragm.

As we mentioned above, interoception and body awareness are often used interchangeably (Mehling et al., 2009). Accordingly, the questionnaires listed in the review about body awareness of Mehling and his colleagues from 2009 can be also considered as questionnaires assessing interoception (Mehling et al., 2009).

Among the questionnaires listed by Mehling et al. (2009), the Body Awareness Questionnaire (BAQ) (Köteles, 2014; Shields et al., 1989). The reliability and the convergent and discriminant validity of BAQ is supported by various authors (Mehling et al., 2009). As BAQ is used in three study out of four (Study 1, 2 and 4) of this dissertation, I will not introduce it in more details. (Regarding its temporal stability and relation to measures of interoceptive sensibility, see Study 1, Ch.2; its relation to somatosensory amplification and symptom report see Study 2, Ch.3; and finally, its relation to subjective well-being see Study 4, Ch.5.)

There are several other questionnaires that were not mentioned by the above mentioned review (Mehling et al., 2009), such as Body Sensations Questionnaire (Chambless, Craig, Bright, & Gallagher, 1984), Body Vigilance Questionnaire (Antony, Meadows, Brown, & Barlow, 1994; Mueller, Telch, & Curry, 1992) or the Physiological Experiences Questionnaire (Rapee, Ancis, & Barlow, 1988), due to the specific exclusion and inclusion criteria set by the authors.

The Interoceptive Consciousness subscale of the Eating Disorder Inventory (Garner et al., 1983) is also commonly used to assess interoceptive sensibility, especially among patients with eating disorder. One of the most recent and already well-known questionnaire is the Multidimensional Assessment of Interoceptive Awareness (Mehling et al., 2012), which already has an updated version (Mehling, Acree, Stewart, Silas, & Jones, 2018).

Body awareness and interoceptive sensibility

As I have mentioned above, body awareness is used by some authors as a synonym for interoception (Mehling et al., 2009). The term originally describes the attentiveness to normal, nonemotive bodily processes (Shields et al., 1989), which is not necessarily the case in the above mentioned questionnaires. The Private Body Consciousness scale (Miller et al., 1981), for example (as Shield et al. pointed out, 1989), involves items describing emotion-related sensations, such as dry mouth or throat.

This recent dissertation reflects well the general confusion in the literature, and also how the view of the author and of her co-authors changed through the years. Study 1 (Ch.2, Ferentzi, Drew, Tihanyi, & Köteles, 2018) describes interoceptive sensibility assessed with the Body Awareness Questionnaire (BAQ) as ‘body awareness’, a construct that is only “closely related” to interoceptive sensibility (Ferentzi, Drew, Tihanyi, & Köteles, 2018, p.102). Study 2 (Ch.3.) also refers to the construct measured with BAQ as ‘body awareness’ (Ferentzi et al., 2017). Study 4, however, explicitly argues that body awareness and interoceptive sensibility are the same constructs with different names, and considers BAQ as an appropriate measure of subjective aspect of interoception (Ferentzi et al., 2019; see below in details).

1.4. Dimensions of interoception – terminology and relation

How do the above described dimensions, i.e. interoceptive accuracy and sensibility relate to each other? According to the majority of the empirical studies, interoceptive sensibility (measured with self-rated questionnaires) and accuracy (measured with behavioral/sensory tasks) are not associated with each other (Ainley & Tsakiris, 2013; Emanuelsen, Drew, & Köteles, 2015; Garfinkel, Seth, et al., 2015; Khalsa et al., 2008; Yoris et al., 2015). Although the problem itself has been recognized much earlier (McFarland, 1975; Whitehead et al., 1977), the necessary conceptual clarification started only years later (Ceunen et al., 2013; Garfinkel & Critchley, 2013), and have not been finished yet. Dimensions of interoception have been called various different names, such as (metacognitive) awareness, sensitivity, sensibility and accuracy (see Table 1.A); different scholars and research groups naming the same construct differently, or not sticking to the terminology that they applied before (Ceunen et al., 2013; N. A. Farb et al., 2015; Garfinkel & Critchley, 2013; Mehling, 2016; Yoris et al., 2015).

Table 1.A: The most commonly applied terms for the main dimensions of interoception in the literature

Source	General interoceptive ability	Assessed with sensory measures	Metacognitive awareness of interoceptive accuracy	Measured with self-rated questionnaires
Ceunen, Van Diest, & Vlaeyen, 2013	–	interoceptive accuracy	–	interoceptive awareness
Garfinkel & Critchley, 2013	–	interoceptive sensitivity	metacognitive interoceptive awareness	interoceptive sensibility
Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015	–	interoceptive accuracy	interoceptive awareness	interoceptive sensibility
Yoris et al., 2015	–	interoceptive sensitivity	–	metacognitive interoception
Farb et al., 2015	interoceptive awareness	interoceptive accuracy	–	interoceptive sensibility
Mehling, 2016	interoceptive awareness	interoceptive accuracy	interoceptive confidence	interoceptive sensibility

In this recent dissertation, the sensory aspect of interoception is systematically called 'interoceptive accuracy' or ‘interoceptive sensitivity’ (Study 1-3., Ferentzi, Bogdány, et al., 2018; Ferentzi, Drew, Tihanyi, & Köteles, 2018; Ferentzi et al., 2017). In Study 4 (Ferentzi et al., 2019), only the term ‘interoceptive accuracy’ has been used; and to avoid confusion, the same terminology is used in the Introduction and in the Discussion.

The description of the self-rated measure assessed with questionnaires is ‘interoceptive awareness’ or ‘interoceptive sensibility’ in Study 1-3 (Ferentzi, Bogdány, et al., 2018; Ferentzi, Drew, et al., 2018; Ferentzi et al., 2017). The construct is named only ‘interoceptive sensibility’ in Study 4 (Ferentzi et al., 2019), and through the Introduction and Discussion. Table 1.B summarizes the terminology of the dissertation.

Table 1.B: Terms used for the main dimensions of interoception in this dissertation

Chapters of the dissertation	Assessed with sensory measures	Measured with self-rated questionnaires	Note
Study 1 (Ch.2)	interoceptive accuracy or sensitivity	interoceptive awareness or sensibility	BAQ is considered as a measure of body awareness
Study 2 (Ch.3)	interoceptive accuracy or sensitivity	*not applicable*	BAQ is considered as a measure of body awareness
Study 3 (Ch.4)	interoceptive accuracy or sensitivity	interoceptive awareness or sensibility	*not applicable*
Study 4 (Ch.5)	interoceptive accuracy	interoceptive sensibility	BAQ is considered as a measure of interoception
Introduction and Discussion (Ch.1 and Ch.6)	interoceptive accuracy	interoceptive sensibility	BAQ is considered as a measure of interoception

The relative inconsistency of the applied terminology of the dissertation reflects well that there is no consensus in the literature regarding the terms: we changed the terminology under the pressure of the reviewers of our papers, as they insisted to follow the terminology of certain papers. This was particularity prominent in the case of BAQ, more precisely whether it can be interpreted as an assessment of interoception.

It is important to emphasize the already mentioned fact that the applied terminology of the literature investigating various issues of interoception is far from being consistent. Table 1.A above introduces only those main dimensions of interoception that are frequently mentioned through this paper (and generally, in the literature), and where the inconsistency is the most prominent and apparent. Additionally, I listed in Table 1.A only the most significant papers of the debate on the subject of the interoceptive dimensions (i.e. on the distinction of the subjective self-reported and the sensory, behavioral assessment).

There are papers, however, that either do not use the terminology introduced in Table 1.A, or are not consistent with any of the above described nomenclature. For example some authors did not apply any of the expressions of ‘accuracy’, ‘sensitivity’, ‘awareness’, or ‘sensibility’ when they investigated the learning and recall of interoceptive stimuli (DeVille et al., 2018). It is the same in the areas that are closely linked the clinical application, such as the investigation of the urinary functions (Abrams et al., 2003). Other papers are just simply do not apply the above introduced terminology, for example they talk about interoceptive awareness when they describe the sensory measures of interoception (Suschinsky & Lalumière, 2012, 2014). This might not be particularly misleading, if one takes into account the exact operacionalization applied.

Last but not least, I would like to point out two common inconsistencies of the literature. Firstly, in Table 1.A, interoceptive accuracy and sensitivity is mentioned interchangeably. Accordingly, these expressions were described above as synonyms. In some cases, however, ‘accuracy’ might be more adequate than ‘sensitivity’, and vice versa. For example, when the level of correctness is involved (like in the calculation of the mental heartbeat tracking score), ‘accuracy’ might be an appropriate expression. In other cases, however, for example when we talk about bowel movements, pain or bitterness, there is not correct sensory level, and therefore ‘sensitivity’ might be more appropriate. When both types of sensory channels are involved, for the sake of simplicity often only one of the expressions is mentioned which might be misleading. In this doctoral thesis (i.e. in the *Introduction* and in the *Discussion*, see: Table 1.B), when I talk about the sensory interoceptive ability (i.e. that is investigated with sensory/behavioral tasks) generally, I will use the term ‘accuracy’.

Secondly, another common misunderstanding is when only a single interoceptive sensory modality is investigated, but the final conclusion of the paper talks about ‘interoception’ without any further specification, assuming that the result can be generalize over all interoceptive channels. This is partly only a question of the used terminology, and not an underlying conceptual mistake; still, it might be misleading for readers that are note familiar with the literature.

There are some attempts to distinguish more than three dimensions of interoception, and to provide a comprehensive summary of the main aspects and phenomenons (N. A. Farb et al., 2015; Khalsa et al., 2018; Quadt, Critchley, & Garfinkel, 2018). Unfortunately, these attempts are far from being consistent with each other regarding both the applied terminology and both the complexity of the investigation. Similarly to these attempts, Table 2 aims to summarize some of the most commonly used concepts and terms of interoception. It is not intended, however, to provide a comprehensive summary of the expressions and their definitions that makes clear all the inconsistencies of the literature. This overview reflects how the concepts of interception are defined and applied in this recent doctoral thesis.

Table 2: The most commonly used concepts and the applied terms of interoception

Feature	Description
Accuracy	Monitoring of body sensations (state-like; assessed with sensory/behavioral tasks) also called 'sensitivity'
Attention	The observation of body sensations (e.g. simple attention tasks are used to investigate interoception in fMRI)
Awareness	Has multiple meaning, depending on the author (see Table 1.A for details); It involves subjectivity of the perception
Detection	Presence or absence of conscious report
Discrimination	The differentiation between sensations (tasks requiring yes/no answers; applying signal detection)
Insight	Metacognitive evaluation of experience/performance also called 'awareness' (e.g., confidence-accuracy correspondence)
Magnitude	Perceived intensity of a certain sensation (usually assessed by visual analogue scale) Also considered by some authors as a measure of accuracy/sensitivity
Sensibility	Self-perceived ability or tendency or ability to focus on body sensation (state-like or trait-like; assessed by self-rated questionnaires) also called 'awareness'

Note: the content of the table is based mainly on the following papers: (N. A. Farb et al., 2015; Garfinkel, Seth, et al., 2015; Khalsa et al., 2018; Quadt et al., 2018; Vaitl, 1996).
A more detailed overview of the terminology of the main dimensions of interoception is presented in Table 1.A.

1.5. Interoception and health

What is the relevance of interoception? What are the benefits and disadvantages of a certain level interoception? In the literature, there two constracting views concerning this subject: one argues for the advantages of high interoception level, the other for its harmful nature.

According to the view arguing for harmfulness, on the one hand, physiological processes that are not conscious are non-conscious for a reason. It is superfluous to have information about processes, that can be controlled and regulated automatically, without conscious attention too; in fact, it might be even harmful, as human attention does not have endless resources (Ádám, 1998). Accordingly, paying attention to physical signals has been considered as maladaptive, that could even cause anxiety, hypochondriasis, irritable bowel syndrome, or panic disorder (Ádám, 1998; Mehling et al., 2009; Tihanyi, Sági, Csala, Tolnai, & Köteles, 2016).

Other authors, on the other hand, argued that interoception and body awareness (defined in the broad sense) provide the base of the self (Ádám, 1998; Cameron, 2002; Damasio, 1999, 2010; Rogers, 1959). According to Damasio (1994, 1999) and the followers of his viewpoint monitoring the signals and signs of the own body helps to behave and act in a congruent way, in accordance with our true emotional state.

The perception of the bodily processes is an active process, which is influenced beside of the bottom-up processes by many other top-down processes of the central nervous system, such as attention, expectations, or schemes, and also by situational factors and mood (Pennebaker, 1982, 1994). According to Pennebaker (Pennebaker, 1982, 1994), in the screening of the visceral input, the so called schema-driven selective search plays a significant role. The information that is in accordance with the current expectation is allowed to enter consciousness; while everything that is contradictory will be filtered out. There are certain factors, that might weaken this filter system, and consequently, signals might enter the system and become conscious that would otherwise only be processed at a lower level of the nervous system (Deary, Chalder, & Sharpe, 2007; Rief & Barsky, 2005). Moreover, the actual content of consciousness is not only influenced by the sensory information, but also by previous events and states stored in the memory, or generally speaking, in the body (Damasio, 1994). Therefore, it may happen that it is not the effect of the current body state that becomes dominant; that is, sensations and symptoms might appear with no physiological background (Brown, 2004, 2006).

This phenomenon is very common: some authors estimate that about 25-60% of the complaints reported to the physicians have no physiological explanation, and only in the minority of such cases can be explained by psychiatric conditions (Brown, 2004; Kroenke & Swindle, 2000). These subjective symptoms are the so called medically unexplained symptoms (Rief & Broadbent, 2007; R. C. Smith et al., 2003). This phenomenon might effect the performance in the heartbeat perception task. In a review that investigated the relation between heartbeat perception and panic disorder, the authors suggested that individuals and certain patient groups might differ in attention distortion or in the tendency to interpret certain body signals more likely as heartbeats (Ehlers & Breuer, 1996).

As we saw above, body awareness originally has been defined as the nonemotive attentiveness to normal body signals (Shields et al., 1989), which can be interpreted as interoception in a broader sense. Recently, a new approach is getting more and more popular that emphasize the importance of nonevaluative body focus in clinical context, meaning both in everyday life and therapy (Bakal, 1999; N. A. Farb et al., 2015; Fogel, 2013; Mehling et al., 2011). Additionally, some authors say that our relation to our own body is not as tight and positive as it use to be, blaming mainly the civilized, modern society and lifestyle, that often requires the suppression of basic bodily needs, like the urge to eat or to urinate (Fogel, 2009; Totton, 2011). From this point of view, body awareness or interoception is not only about the perception or detection of bodily signals, but also their active monitoring, which might lead to adaptive behavioral responses, like visiting the doctor or healthier lifestyle (Bakal, 1999; Bakal, Coll, & Schaefer, 2008). Based on this thought, there are numerous body-mind-techniques (such as exercise, yoga, breathing, or relaxation; sometimes in the framework of the somato-psychotherapetuic approach) that aim to develop the ability to focus on the body in a nonevaluative, neutral way (Totton, 2003). Some further aspects of this topic is discussed below (see Study 1, Ch.2), when studies about the temporal stability of interoceptive accuracy and sensibility are introduced is more details.

1.6. Predictive coding – a model of information processing

So far, I have discussed the modalities and main dimensions of interoception, and also various conceptually different approaches considering its relation to health and illness.

How the elementary building blocks of the interoceptive sensations might develop into (more or less) integrated, conscious interoceptive information, will be explained below.

In the following, I will introduce a recently developed model that aim to explain the possible ways of the processing of interoceptive signals. The predictive coding model was originally developed to explain how visual information is processed (Friston, 2005; Friston, Kilner, & Harrison, 2006), and applied later in the context of interoception (Edwards, Adams, Brown, Pareés, & Friston, 2012; Sel, 2014; Seth, Suzuki, & Critchley, 2012).

The model of predictive coding describes a hierarchical system of information processing (Friston, 2005). An inherent part of the sensory process is interpretation: if sensory change occurs, the system attempts to figure out its cause. This is a very important task of the perceptual system, because if it is able to predict the cause of the incoming information, the system has more chance to successfully adapt to the environment. This is not a simple task, as changes might have multiple causes, and different causes can results in more or less identical changes. Additionally, the decision has to be made quickly, to be as efficient as possible in situations that might be life-threatening.

According to the predictive coding model, the system always has a prediction (perceptual inference) concerning the cause of the sensory events, and it is based partly on previous experiences, partly on genetic predispositions. The incoming information (input) might confirm this, or on the contrary, it might contradict with the expectation (this is surprise). In the latter case, the system can modify the prediction (called prior), or alternatively, the rate or method of the sampling of the incoming information (Friston, 2005; Friston et al., 2006).

The system has multiple levels with reciprocal bottom-up and top-down processing. The forward and backward connections are, however, asymmetrical: while forward connections provide new information (i.e. they drive), the backward connections are also able to modulate (i.e. they have both driving and modulator function), making by this the perceptual learning possible. At each level of the hierarchy, the new information delivered by the forward connections is compared with the already existing model (i.e. prediction) of the system (Friston, 2005).

If the actual and the predicted information does not fit (surprise), the system produces 'prediction error' that will change the prediction (or the selected input); and this new version of the prediction will be the basis of comparison one level below. The goal of the organism is to minimize errors as much as possible in the whole hierarchy of the system, i.e. to make the prediction as good as possible (Friston, 2009). The correction of the prediction error can take two forms. One the one hand, it is possible to fit the prediction better to the incoming information; on the other, it is also possible to fit the incoming information is selected, to fit the prediction. Thus, according to the model, perception (including interoception) is an active process (Feldman & Friston, 2010; Friston, 2009).

It is important to point out that the predictive coding model, as a framework of computational neuroscience, does not initially take into account automatic subjective evaluations, i.e. emotions. The main focus of the model introduced below is (R. Smith & Lane, 2015), on the other hand, how conscious and unconscious emotional states emerge, and what are the underlying neural structures. This more recently developed model will be introduced in more details in the *Discussion* (Ch.6).

The above described model of predictive coding might be able to explain some significant aspects of the relation between interception and health; among others, functional somatic syndromes (Edwards et al., 2012; van den Bergh, Witthöft, Petersen, & Brown, 2017). I also have to point out, that even if the predictive coding model was initially designed to explain the processing of visual information (and emotions initially do not have a significant role), there are some more recent attempts to adapt the model in specific situations involving interoception, for example in emotional processes (Sel, 2014; Seth, 2013; Seth & Friston, 2016).

1.7. The aim of the dissertation

The aim of this dissertation is to investigate some of the key issues related to interoception, namely its temporal stability, the relation between interoceptive dimensions and modalities, and their connection to health and illness-related psychological constructs.

In the literature, interoception is often mentioned without any further specification or adjective which makes the misleading impression that it is a unitary construct. The conceptualization of interoception and the interpretation of the empirical results requires careful re-consideration of this subject. Seemingly, these topics are mainly methodological issue, but the consequences, as we will see, reach far beyond the problems of measurement.

The first big topic of my thesis is the relation of the two main dimensions of interoception, namely self-rated interoceptive awareness and interoceptive accuracy assessed with sensory task. This will be the focus of Study 1. (Ch.2, Ferentzi, Drew, et al., 2018). As I have mentioned before (see Ch.1.4), interoceptive awareness and accuracy did not relate to each other according to the majority of the literature (e.g. Ainley & Tsakiris, 2013; Garfinkel, Seth, et al., 2015; Khalsa et al., 2008). Although this problem has been recognized much earlier (McFarland, 1975; Whitehead et al., 1977), the necessary conceptual clarifications have started only quite recently (Ceunen et al., 2013; Garfinkel & Critchley, 2013). It is important to point out, however, that the conclusion of independence based on cross-sectional studies, which do not take spontaneous fluctuation into account. Additionally, the temporal stability of the two constructs has been investigated mainly in studies with a focus of developing various aspects of interoception (see for more details the *Introduction* of Study 1, Ch.2.1). Even if only the control group is taken into account, this design might lead to different results as a longitudinal study designed to investigate temporal stability that is not influenced by any intervention.

The second bigger topic that my thesis aims to investigate is the relation of various interoceptive modalities. This will be the focus of Studies No.2-3 (Ch.3-4, Ferentzi, Bogdány, et al., 2018; Ferentzi et al., 2017). As it has been explained above (see Ch.1.2), interoceptive accuracy has various modalities or interoceptive channels. According to the majority of the studies (with some exceptions, e.g. Herbert et al., 2012; Whitehead & Drescher, 1980), these interoceptive modalities do not correlate. The number of the papers focusing on this topic, however, is limited; just like the number of the investigated interoceptive channels (see: Ch.1.2, and the *Introduction* of Ch.3-4).

The third and last big topic of my thesis is the investigation of the correlates of interoception, those that are (directly or indirectly) related to health and illness. As we have seen above (Ch. 1.5), in the literature, both the negative and positive consequences of high interoceptive ability are well-represented. It is particularity interesting to investigate this topic from a multidimensional and multimodal perspective. Study 2 (Ch.3, Ferentzi et al., 2017) involves somatosensory amplification, while Study 4, (Ch.5, Ferentzi et al., 2019) investigates subjective well-being. In both studies, interoception is investigated both with self-rated measures and sensory assessment (multidimensionality), and interoception itself is also grasped by multiple assessments (multimodality).

2. Interoceptive accuracy and body awareness – Temporal and longitudinal associations in a non-clinical sample (STUDY 1)[3]

2.1. Introduction

Interoception, the sense of the physiological condition of the body (Craig, 2002) has a significant role in psychological functioning. For example, it provides the basis for the self and self-awareness, has a significant contribution to decision making (Ainley, Tajadura-Jiménez, Fotopoulou, & Tsakiris, 2012; Damasio, 1994, 1999; S Epstein, 2003; Rogers, 1951), and it appears to be altered in several disorders, for example in somatoform (Schaefer, Egloff, & Witthöft, 2012) and panic disorders (Van der Does, Antony, Ehlers, & Barsky, 2000).

Genuinely, interoception is defined as the sensation of various internal signals arising from the body (Craig, 2009, 2015; Critchley & Harrison, 2013). Although there is a general agreement among researches that it is a multidimensional construct (N. A. S. Farb et al., 2015; Ferentzi et al., 2017; Khalsa & Lapidus, 2016), there is no consensus regarding the number and the name of the components. First, 'interoceptive accuracy' (Ceunen et al., 2013; N. A. S. Farb et al., 2015; Garfinkel, Seth, et al., 2015; Mehling, 2016) or 'interoceptive sensitivity' (Garfinkel & Critchley, 2013; Yoris et al., 2015) refer to the accuracy of perception/detection of interoceptive signals. It is assessed with behavioral (i.e. objective) measurements, such as the heartbeat perception or tracking task and the detection or discrimination tasks (Schandry, 1981; Whitehead et al., 1977). Second, 'interoceptive awareness' (Ceunen et al., 2013) or 'sensibility' (N. A. S. Farb et al., 2015; Garfinkel & Critchley, 2013; Garfinkel, Seth, et al., 2015; Mehling, 2016), also called 'metacognitive interoception' (Yoris et al., 2015) is measured with questionnaires, and defined as the self-reported or perceived interoceptive ability. Finally, some authors distinguish a further aspect, called 'interoceptive awareness', and also 'metacognitive awareness of interoceptive accuracy', e.g. confidence-accuracy

3 The present chapter is the exact copy of the following paper: Ferentzi, E., Drew, R., Tihanyi, B. T., & Köteles, F. (2018). Interoceptive accuracy and body awareness – Temporal and longitudinal associations in a non-clinical sample. *Physiology & Behavior*, *184*(Supplement C), 100–107. https://doi.org/10.1016/j.physbeh.2017.11.015

correspondence (Garfinkel & Critchley, 2013; Garfinkel, Seth, et al., 2015). This paper does not focus on this third aspect, and refers to self-reported interoception as interoceptive awareness (IAw). There is an additional concept, called 'body awareness' that has been developed before the modern definition of interoception. Body awareness, that refers to the beliefs about one's sensitivity to normal body processes and changes (Shields et al., 1989), represents a more integrative approach to subjective body experience, that is generally based on the integration of several interoceptive sensory channels, as well as exteroceptive modalities. According to a recent definition (Mehling et al., 2009, p. 4), "Body awareness is the perception of bodily states, processes and actions that is presumed to originate from sensory proprioceptive and interoceptive afferents and that an individual has the capacity to be aware of." As the definition emphasizes the involvement of perceptual processes and conscious awareness, this construct shows considerable overlaps with the dimension of interoception called interoceptive awareness or sensibility. The construct of body awareness can be very well explained by the modern evolutionary approach to interoception, which emphasizes the adaptive importance of multimodal integration of body related information in the mid-insula (Craig, 2015). This integrated feeling of the body plays a role in homeostatic regulation, the generation of the feeling of being alive, and also in the emergence of emotional feelings (Craig, 2015). It is not clear, however, how individual interoceptive channels may contribute to and change body awareness. The aim of this study is to investigate the temporal stability of and the relationship between interoceptive accuracy (IAc) and a related concept, body awareness (BA).

For the measurement of IAc with the focus on the heartbeats, two major approaches have been developed. The tracking or perception methods compare the number of the perceived and measured heartbeats (McFarland, 1975; Schandry, 1981); while during the detection tasks subjects discriminate between their own heartbeats and rhythmic external signals (Clemens, 1984; Kleckner et al., 2015; Whitehead et al., 1977). Both tracking (Ring & Brener, 1996; Ring et al., 2015) and discrimination methods (Knapp et al., 1997; Pennebaker, 1982) were criticized for being influenced by factors that are not inherent part of interoception, and it was questioned also whether they measure the same phenomenon (Garfinkel, Seth, et al., 2015; Knoll & Hodapp, 1992; Pennebaker & Hoover, 1984). This paper does not aim to decide this debate, but distinguish between the two methods consequently.

IAc measured with the heartbeat tracking and detection methods is described by previous studies as a stable trait-like characteristic (Ainley, Maister, Brokfeld, Farmer, & Tsakiris, 2013; Hart et al., 2013). According to the literature, there are three major arguments that support this notion. First, only the minority of the interventions designed to manipulate IAc had been successful. Second, IAc is associated with trait-like psychological variables. Third, there are findings that directly demonstrate the temporal stability of IAc. We critically review the empirical evidence supporting these arguments and investigate to what extent they really support the stability and trait-likeness of interoceptive accuracy.

Concerning the first argument, the most direct way to improve IAc is to provide feedback to the participants on their performance (Edward S. Katkin, 1985; Edward S. Katkin et al., 1981). Empirical studies demonstrated, however, that such changes of IAc have to be interpreted cautiously, as the improvement may be only due to participants' updated knowledge or belief about heart rate (Ring & Brener, 1996; Ring et al., 2015). Schaefer and her colleagues developed a new method to improve heartbeat tracking using feedback (Schaefer, Egloff, Gerlach, & Witthöft, 2014), but avoiding the pitfalls of previous studies (Schandry & Weitkunat, 1990) mentioned above. Although there was no significant difference between intervention and wait list in the level of IAc, a significant reduction in state symptoms of somatoform disorders was observed after training, which was interpreted as an indicator of improvement of heartbeat perception (Schaefer et al., 2014). There are other methods and techniques that are assumed to improve IAc, but the majority of the studies show poor effectiveness. For example, there was no difference between long-term Buddhist meditators (N = 11) and nonmeditators (N = 17) in IAc measured with the detection task (Nielsen & Kaszniak, 2006). A study, also using detection task with a bigger sample size (N = 16 Kundalini and 13 Tibetan Buddhist meditators) and a matched control (N = 15) found similar results (Khalsa et al., 2008). Other cross-sectional studies using various tracking tasks also reported null findings (Melloni et al., 2013; Otten et al., 2015). A longitudinal research did not find any change in cardiac perception following either a one week long (N = 80), or an eight weeks long (N = 19) mindfulness meditation training (Parkin et al., 2013). Moreover, although cognitive-behavior therapy reduced the symptoms of panic disorder, it did not change the accuracy of heartbeat tracking (Antony et al., 1994). Similarly, in a four weeks long intervention study on a comprehensive behavioral program, the accuracy of heartbeat perception improved from 0.498 to 0.591 (N = 42), but the change did not reach the threshold of significance (Mussgay, Klinkenberg, & Rüddel, 1999). One of the studies that showed a significant improvement of IAc measured with the tracking task involved two subsamples (N = 77 and 79) receiving contemplative training for 9 months, and a third group (N = 78) participating in social-affective training for 3 months (Bornemann & Singer, 2017). Differences with small to medium effect sizes were found after 6 months (Cohen'sd = 0.173 after 6 months, and 0.273 after 9 months). Another recent study investigated the effect of an 8-week body scan intervention on the heartbeat perception ability (Fischer et al., 2017), and reported mixed results. One of the sub-studies found no difference between the body scan group (N = 25) and the control group (N = 24) that listened to an audio book; while the other sub-study found increased mean IAc scores (significant change from 0.53 ±0.20 to 0.65 ± 0.19; N = 18) in the body scan group, but not in the inactive control group (N = 18).

There is another line of research aiming to temporarily manipulate IAc by varying experimental conditions. For example, manipulations like the inclusion of a mirror (Ainley et al., 2012; Weisz et al., 1988), or asking the participants to look at a photograph of their own face (Ainley et al., 2013) were successfully utilized both with heartbeat tracking and discrimination methods. There are a few studies that applied biological manipulations to modulate the level of IAc. In one study, isoproterenol infusion was used to increase the heart rate. After treatment, altered cardiac sensations were found in all 15 participants, in a dose-dependent manner (Khalsa, Rudrauf, Sandesara, Olshansky, & Tranel, 2009). Another research investigated the effects of variations in stroke volume, and found that it did not influence either heartbeat detection, nor the location of the sensation (Ring, Liu, & Brener, 1994). Other studies investigated the impact of stress; for example, female participants showed a significant decline of heartbeat detection during a demanding mental arithmetic task (Fairclough & Goodwin, 2007). The anticipation of public speech marginally improved heartbeat perception in a sample of subjects with high and low social anxiety (Stevens et al., 2011); similar results were reported investigating a non-anxious sample (Durlik, Brown, & Tsakiris, 2014). On the other hand, IAc measured by tracking task did not increase but decreased after the experience of social exclusion (Durlik & Tsakiris, 2015). Finally, a recent study indicates that directing the attention to romantic partners' face during the heartbeat perception task improves the accuracy scores of people with low IAc (Maister, Hodossy, & Tsakiris, 2017). In summary, there is limited evidence indicating that situational factors might cause temporary fluctuations in IAc. The results of training are controversial: some methods did not change the level of IAc significantly, while in some cases it is not clear, whether the change in heartbeat perception/detection can be explained by improved IAc.

As for the second argument (i.e. IAc is related to temporally stable characteristics), a review on heartbeat perception and detection techniques in anxiety and anxiety disorders included six studies on trait anxiety and IAc, and found a significant association with small to medium weighted mean effect size ($d = 0.37$, $SD = 0.13$, 95% CI [0.1-0.64], $N = 202$) (Domschke, Stevens, Pfleiderer, & Gerlach, 2010). A research that had not been included in this review reported similar findings ($r = 0.20$, $p = 0.028$) (Pollatos, Traut-Mattausch, & Schandry, 2009), while another study did not find a significant connection ($r = -0.09$, $p = 0.36$) (Dunn, Stefanovitch, et al., 2010); both studies used tracking task. Findings regarding alexithymia, another trait-like characteristic, are less consistent. There was no significant correlation between heartbeat perception and different dimensions of alexithymia as assessed by the Bermond/Vorst Alexithymia Questionnaire ($N = 60$) (de Galan, Sellaro, Colzato, & Hommel, 2014). Conversely, there was a moderate inverse association between IAc measured with tracking task and the scores of the Toronto Alexithymia Scale (TAS) ($p = -0.37$, $r < 0.01$, $N = 155$) (Herbert, Herbert, & Pollatos, 2011). Furthermore, a study found that antisocial behavior, another temporally stable feature, predicts reduced heartbeat detection scores (Nentjes, Meijer, Bernstein, Arntz, & Medendorp, 2013). On the other hand, IAc was not related to borderline disorder (Hart et al., 2013) assessed by detection task, trait mindfulness (Parkin et al., 2013), or any of the Big Five personality factors (Ferentzi et al., 2017) measured with tracking tasks. In summary, associations between IAc and trait-like characteristics are not conclusive regarding the temporal stability of IAc. On the one hand, this is due to the empirical evidence presented above, but also to the very nature of this popular argument. In more detail, from the lack of association between two traits can not be directly concluded that any of them is not a trait. Even for the studies that reported positive associations, the existence of a third variable explaining the connections can not be excluded.

Finally, we have empirical findings that directly (i.e. through multiple measurements) support the temporal stability of IAc. Pollatos and her colleagues estimated a test-retest reliability of the tracking task up to 0.81, but the exact sample size and the time interval between the measurements were not specified (Herbert et al., 2011; Pollatos, Traut-Mattausch, Schroeder, & Schandry, 2007). A study investigating 42 patients receiving therapy belonging to various diagnostic categories reported strong test-retest correlation of heartbeat perception in a four weeks period ($r = 0.58$, $p < 0.001$) (Mussgay et al., 1999). Parkin and her colleagues, who investigated the effect of mindfulness training, found high test-retest reliability of the tracking task after a week in two studies ($N = 60$ in each; $r = 0.70$ and $r = 0.80$, $p < 0.001$ in both cases), and a somewhat lower value ($N = 19$, $r = 0.65$, $p < 0.01$) in a third one, measuring IAc after 8 weeks (Parkin et al., 2013). On the other hand, a study using a new method to improve IAc (see above) found increased detection ability both in the training and the control group (Schaefer et al., 2014). The analysis demonstrated a significant main effect of time ($N = 52$; $F(1,50) = 17.68$, $p \leq 0.001$, $\eta^2 = 0.261$), IAc increased in the total sample from 0.58 ± 0.25 to 0.66 ± 0.23. A study investigating a big sample of children ($N = 1657$) between age 6 and 11 found relatively low stability of heartbeat perception ($\beta = 0.33$, $p < 0.001$) after a year (A. Koch & Pollatos, 2014). A recent study that investigated the effects of body scan included a small inactive control group ($N = 18$) (Fischer et al., 2017). The change of IAc assessed by tracking task over 8 weeks did not reach the level of significance. The largest non-intervention adult sample was the control group ($N = 84$) of a study on IAc and contemplative mental training (Bornemann & Singer, 2017). After 9 months, the mean heartbeat perception score changed from 0.639 ± 0.240 to 0.664 ± 0.246 (not significant). In summary, the majority of the results that show the temporal stability of IAc assessing an adult sample are provided by intervention studies failing to improve IAc significantly. However, intervention studies do not represent a methodologically sound procedure to assess temporal stability. Although a no-intervention (control) group was included in several studies, participants might have received instructions that biased the results.

Interoceptive accuracy, i.e. the objectively measured ability to perceive heartbeats is only one aspect of interoception (Ceunen et al., 2013, 2016; N. A. S. Farb et al., 2015). Among the two self-reported constructs, interoceptive awareness regarded as another aspect, while body awareness as a closely related construct. The majority of the empirical studies found no significant associations between IAc and the self reported measures of BA and IAw. For example, scores of the *Autonomic Perception Questionnaire* did not show any or only low correlations with objective interoceptive tasks (McFarland, 1975; Whitehead, Drescher, & Blackwell, 1976; Whitehead et al., 1977), just like the Private Body Consciousness subscale of the *Body Consciousness Questionnaire (Ainley & Tsakiris, 2013; Weisz et al., 1988)*. Heartbeat tracking scores did not correlate with the *Multidimensional Assessment of Interoceptive Awareness* (MAIA) (Calì, Ambrosini, Picconi, Mehling, & Committeri, 2015), except with the subscale called Attention regulation ($r = 0.20$, $p = 0.020$, $n = 135$). Similar findings were reported for the *Body Awareness Questionnaire* (BAQ) using the tracking task (Emanuelsen et al., 2015; Ferentzi et al., 2017), and the *Body Perception Questionnaire* scores assessed by heartbeat detection (Critchley, Wiens, Rotshtein, Öhman, & Dolan, 2004). A recent study applying a new variation of the heartbeat perception task found no correlation with the scores of the *Body Sensations Questionnaire* and the *Physical Concern Index* (Yoris et al., 2015). Finally, the selection of participants with high accuracy (mean IAc score: 0.83 ± 0.08, $N = 40$) by using median split method resulted in a correlation of $r = 0.28$ ($p = 0.078$) between IAc and IAw, the latter measured with the Porges Body Perception Questionnaire (Garfinkel, Seth, et al., 2015).

Empirical findings concerning the temporal stability of BA and IAw are also controversial. For example, BAQ showed high test-retest reliability ($r = 0.8$, $N = 70$) over a two weeks period of time (Shields et al., 1989). On the other hand, BA and IAw can be affected by body-related activities, which is supported by both cross-sectional and longitudinal studies. Aerobics instructors scored significantly higher on BAQ than the comparison group (Shields et al., 1989). Following a 3 months long hatha yoga training, the BAQ-scores increased in the yoga group ($N = 17$) compared to the control group ($N = 19$) (Rani & Rao, 1994). A sample of primary care patients ($N = 435$) had significantly lower scores on MAIA than a sample of a body-mind experienced sample ($N = 325$), i.e. students and teachers of mind-body therapies (Mehling et al., 2013). A 3 months long contemplative training improved MAIA scores of five subscales out of eight (Bornemann, Herbert, Mehling, & Singer, 2015). Similarly, depressed patients had higher MAIA scores on four subscales after a brief mindfulness training compared to patients receiving control training (Fissler et al., 2016). On the other hand, the scores of Body Vigilance Questionnaire did not change after the cognitive-behavior therapy that reduced the symptoms of panic disorder (Antony et al., 1994), just like the scores of the Interoceptive awareness subscale of EDI-2 after body scan intervention (Fischer et al., 2017).

Beyond temporal stability issues, our knowledge concerning the association between IAc and IAw/BA is also relatively one-sided. The conclusion that they are independent of each other are drawn mostly from cross-sectional studies (Ainley & Tsakiris, 2013; Calì et al., 2015; Critchley et al., 2004; Emanuelsen et al., 2015; Ferentzi et al., 2017; McFarland, 1975; Weisz et al., 1988; Whitehead et al., 1976, 1977; Yoris et al., 2015), where spontaneous fluctuations could have attenuated a potential association. Taking into consideration the often mentioned role of body focus or body vigilance in interoception (Köteles & Doering, 2016; Pennebaker, 1982; Shields et al., 1989), longitudinal associations are also possible. From a theoretical point of view, higher levels of body awareness should lead to improved accuracy over time, at least in healthy individuals. And the other way around, more sensations from the body can direct attention to the body, which may increase interoceptive awareness as well as body awareness.

The present study investigated the following hypotheses. First, no baseline cross-sectional connection between IAc and BA was expected. Second, both IAc and BA are stable characteristics over a period of two months. Third, BA predicts changes in IAc, and fourth, IAc predicts changes in BA.

2.2. Methods

Participants

The participants of the study were undergraduate and graduate university students of the same university (N = 103, 31% male, 23.34±4.34 yrs), and they belonged to two different subgroups: 44 Hungarians (36.4% male, 21.4±1.67 yrs) and 59 Norwegians

(25.4% male, 24.8±5.09 yrs). The language used (questionnaire and instructions) was Hungarian for the Hungarians, and English for the Norwegians. Norwegian participants were enrolled to a university program offered in English. Participants attended the study either for course credit or signed up voluntarily to participate in a study investigating interoception. The study was approved by the local ethics committee, and all participants signed an informed consent form.

Questionnaires

The *Body Awareness Questionnaire* (BAQ) is an 18-item scale that measures the attentiveness to normal nonemotive body processes. According to a review on self-report measures of body awareness, several studies by various authors support its reliability and validity (Mehling et al., 2009). The internal consistency of the original version was 0.82 (Shields et al., 1989), and it was in the range of 0.81-0.88 for the Hungarian version (Emanuelsen et al., 2015; Köteles, 2014). In our recent study, the Cronbach's alpha was 0.79 at the time of the first measurement, and 0.83 at the second.

Heartbeat perception task

We conducted the heartbeat perception task of Schandry (Schandry, 1981). Participants were in a seated position, and were asked to breathe normally. After 3 min resting participants were asked to count their perceived heartbeats silently during different time periods (30s, 40s and 100s, in random order). During the heartbeat-counting sessions participant were not allowed to take their pulse or use other techniques that might help counting. They were instructed to count uncertain sensation but to refrain from guessing. Participants were not informed neither about the length of the trials, or about their performance. The trial started with a 15 sec long practicing, and there was a 10 sec long break between each interval. Heart rate was measured using the Polar Fitness Test of RS-400 Polar watch and the matching chest strap and transmitter (POLAR WearLink; Polar Electro, Kempele, Finland) (Emanuelsen et al., 2015; Ferentzi et al., 2017; Tihanyi, Ferentzi, Daubenmier, Drew, & Köteles, 2017). IAc was the mean score of the following formula 1–[(|recorded heartbeats – counted heartbeats|)/recorded heartbeats] calculated for each time interval. Resting heart rate (rHR) was calculated from the number of heartbeats during the longest interval (100s).

Body fat measurement

Body composition was measured using a Bodystat® 1500 bioelectrical impedance analysis device (Bodystat Ltd, Ballakaap, UK) that uses two dual electrodes attached to the upper and the lower limbs on the same side of the body. In this widely used approach, body composition is estimated from the electrical impedance of the body.

Procedure

Participants signed the informed consent before the measurements. They filled out the questionnaires on-line prior to the heartbeat perception task (along with other questionnaires that do not interfere with BAQ). Body fat measurement occurred within a week. The second measurement followed after 8 weeks.

Statistical analysis

Data were analyzed using the SPSS v20 software. Based on the results of normality analysis (Shapiro-Wilk test) parametric statistical methods were used throughout the analysis. Homogeneity of the two groups with respect to gender and age, and the comparison of baseline IAc and BA scores were assessed using chi-square test and Student t-test, respectively. Correlation coefficients of the two groups were compared using the Fisher r-to-z transformation method. Differences between the two nationalities with respect to IAc and BA were checked using two separate analyses of variance with gender and age as covariates. To investigate participant with high IAc only, we conducted a median split (Garfinkel, Seth, et al., 2015), resulting a subgroup of 51 participants with a mean IAc score of 0.70±0.15. The first hypothesis, i.e. the lack of cross-sectional connection between IAc and BA, and the second, i.e. the temporal stability of IAc and BA, were checked using Pearson correlation. Hypothesis 3 was investigated using a multiple linear regression analysis with IAc at t2 as criterion variable. Variables were entered in three steps: first control variables (nationality, gender, age, rHR, and body fat), followed by baseline BA at t1, and finally baseline IAc at t1. Hypothesis 4 was estimated using a multiple linear regression analysis with BA at t2 as criterion variable. Similar to the previous analysis, variables were entered in three stepswise: (1) control variables (nationality, gender and age); (2) IAc at t1; (3) BA at t1.

2.3. Results

Descriptive statistics are presented in Table 3. No difference between the two groups of Hungarian and Norwegian students with respect to gender ratio was found ($\chi2 = 1.434$, $p = 0.231$); however, the Norwegian group was significantly older than the Hungarian ($t(101) = -4.323$, $p < 0.001$). Both for interoceptive accuracy and for body awareness, t-test indicated a marginally significant group-level difference at t1 (IAc: $t(100) = -1.940$, $p = 0.055$ BA: $t(97) = 2.044$, $p = 0.044$). The analysis of variance comparing the two subsamples was significant in the case of IS for gender ($F(1,98) = 7.143$, $p = 0.009$), was at the margin of statistical significance for age ($F(1,98) = 3.341$, $p = 0.071$), but not for nationality ($F(1,98) = 1.930$, $p = 0.168$). The ANOVA analysis had no significant results when running for BA (nationality: $F(1,95) = 2.293$, $p = 0.133$); gender: $F(1,95) = 0.506$, $p = 0.479$; age: $F(1,95) = 0.580$, $p = 0.448$).

Interoceptive accuracy and body awareness did not correlate at the time of the first measurement (Hypothesis 1; entire sample: $r = 0.06$, $p = 0.587$, see Figure 1.A; Hungarian sample: $r = 0.16$, $p = 0.336$; Norwegian sample: 0.07; $p = 0.595$). After the median split, body awareness of participants with higher IAc still did not correlate with IAc ($r = -0.234$, $p = 0.106$).

Table 3. Descriptive statistics (means ± standard deviation) in the entire sample and split by group

	Entire sample (N = 103)	**Hungarians (N = 44)**	**Norwegians (N = 59)**
age (yrs)	23.34±4.34	21.4±1.67	24.8±5.09
gender (male)	31%	36.4%	25.4%
IAc at t1	0.48±0.266	0.42±0.252	0.52±0.270
IAc at t2	0.54±0.272	0.55±0.276	0.53±0.272
resting heart rate t1 (bpm)	75.33±15.273	75.59±18.386	75.13±12.630
body fat percent	20.94±6.668	18.98±6.054	21.94±6.791
BA at t1	83.29±12.755	86.43±11.110	81.17±13.436
BA at t2	82.34±12.687	83.25±13.431	81.73±12.236

Note: IAc = interoceptive accuracy; BA = body awareness; t1 = baseline measurement; t2 = second measurement 8 weeks later

Figure 1.A-C. Biplots presenting the relationship between IAc and BA values at different time of measurement

Note: IAc = interoceptive accuracy; BA = body awareness; t1 = baseline measurement; t2 = second measurement 8 weeks later

Figure 1.A Baseline IAc and BA values (N = 98, r = 0.06, p = 0.587)

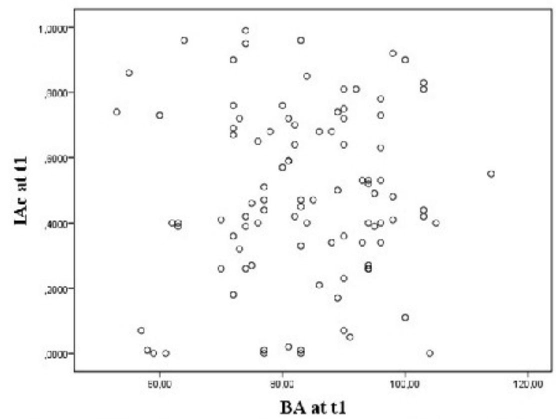


Figure 1.B BA values at t1 and t2 (N = 95, r = 0.73, p < 0.001)

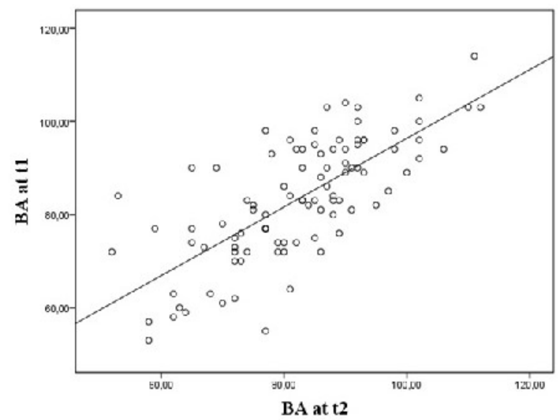
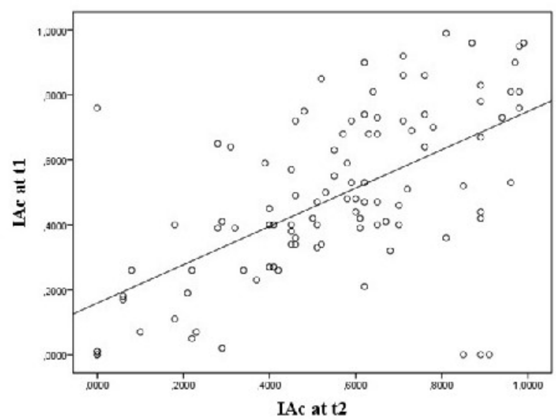


Figure 1.C IAc values at t1 and t2 (N = 102, r = 0.60, p < 0.001)



Test-retest analyses

Concerning body awareness (Hypothesis 2b), Pearson correlation indicated good temporal stability ($r = 0.73$, $p < 0.001$ for the total sample, see Figure 1.B; $r = 0.68$, $p < 0.001$ for Hungarians, and $r = 0.78$, $p < 0.001$ for Norwegians) over the eight-week period. There was no significant difference between the two correlation coefficients ($Z = -0.99$, $p = 0.322$). In the case of interoceptive accuracy (Hypothesis 2a), the correlation coefficients were somewhat lower, but still in the acceptable domain ($r = 0.60$, $p < 0.001$ for the entire sample, see Figure 1.C; $r = 0.60$, $p < 0.001$ for Hungarians, and $r = 0.64$, $p < 0.001$ for Norwegians). Again, no difference between the two coefficients was found ($Z = -0.31$, $p = 0.757$).

The details of the multiple linear regression equation predicting IAc at t2 (Hypothesis 3) are presented in Table 2. The first two equations were not significant. In the third step, when IAc at t1 was entered, the equation explained 44.1% of the total variance ($p < 0.001$). In this equation, IAc at t1 proved to be a significant predictor of IAc at t2, while BA was not.

Table 4. Standardized β-coefficients in the three steps of multiple linear regression analysis predicting IAc at t2

	1st step $R^2 = 0.072$ $p = 0.302$	**2nd step** $\Delta R^2 = 0.035$ $p = 0.085$	**3rd step** $\Delta R^2 = 0.334$ $p < 0.001$
nationality	-0.151	-0.119	-0.195**
gender	-0.070	-0.040	0.107
age	0.134	0.151	0.041
body fat %	-0.095	-0.123	-0.156
resting heart rate at t1	-0.124	-0.144	-0.098
BA at t1		0.192	0.149
IAc at t1			0.620***

Note: **: $p < 0.05$; ***: $p < 0.001$;
IAc = interoceptive accuracy; BA = body awareness; t1 = baseline measurement; t2 = second measurement 8 weeks later

Table 5. Standardized β-coefficients in the three steps of multiple linear regression analysis predicting BA at t2

	1st step **$R^2 = 0.014$** **p = 0.783**	**2nd step** **$\Delta R^2 = 0.006$** **p = 0.472**	**3rd step** **$\Delta R^2 = 0.563$** **p < 0.001**
nationality	-0.109	-0.119	0.026
gender	-0.047	-0.022	0.003
age	0.067	0.050	0.128
IAc at t1		0.083	0.006
BA at t1			0.775***

Note: ***: p < 0.001;
IAc = interoceptive accuracy; BA = body awareness; t1 = baseline measurement; t2 = second measurement 8 weeks later

The details of the multiple linear regression analysis with BA at t2 as criterion variable (Hypothesis 4) are presented in Table 5. The first two equations were not significant. The third one, when BA at t1 was entered explained 58.3% of the total variance ($p < 0.001$). In this final equation, significant predictors of BA at t2 were gender and BA at t1.

2.4. Discussion

In a two-month longitudinal study with the participation of healthy young adults, both interoceptive accuracy (IAc, as assessed by heartbeat tracking ability) and body awareness (BA, as assessed by the Body Awareness Questionnaire) showed good temporal stability. The two constructs were independent of each other, both cross-sectionally and longitudinally.

Our study is the first to show the long-term stability and independency of interoceptive accuracy (IAc) and body awareness (BA) using a longitudinal, non-intervention design. The temporal stability of IAc we found is in line with the results of previous studies that failed to improve it (Antony et al., 1994; Melloni et al., 2013; Mussgay et al., 1999; Otten et al., 2015; Parkin et al., 2013; Schaefer et al., 2014), or changed it only temporarily (Ainley et al., 2013, 2012; Durlik et al., 2014; Durlik &

Tsakiris, 2015; Fairclough & Goodwin, 2007; Stevens et al., 2011). Contrary to IAc, both BA and IAw can be relatively easily affected by body-related activities, like aerobic, yoga, and contemplative training (Bornemann et al., 2015; Mehling et al., 2013; Rani & Rao, 1994; Shields et al., 1989). This is due to the fact, that IAw and BA are assessed by self-report questionnaires and based not only on sensory processes. They both can be influenced to a great extent by the beliefs and attitudes of the subjects. Because the instructions and the total atmosphere of body focused activities emphasize the importance of the body-mind connection, the conscious self-reported awareness of the bodily cues will likely increase. As no such intervention was included in our study, the level of BA did not change either.

The difference between IAw and BA is not consequently defined in the literature. For example, the Body Perception Questionnaire of Porges (Porges, 1993) has been identified as a questionnaire that assesses body awareness (Mehling et al., 2009), while others describe it as an assessment of subjective interoception (Garfinkel, Seth, et al., 2015). The terms BA and IAw have been also used interchangeably (Ginzburg et al., 2015). The difficulties in the definition and application of these concepts can be attributed to the considerable overlaps between them. The perception of interoceptive channels does not occur in a vacuum; body percepts are more or less localized, and they indicate an underlying integrated body representation. Moreover, interoceptive channels and contents (including emotions) are able to alter the perception of other individual channels.

From a clinical point of view, it is important to emphasize that IAc and IAw/BA are not related to each other in healthy individuals. In certain clinical conditions (hypochondriazis/health anxiety, somatoform disorders), however, a negative association between symptoms and IAc was reported (Barsky, Brener, Coeytaux, & Cleary, 1995; Krautwurst, Gerlach, Gomille, Hiller, & Witthöft, 2014; Schaefer et al., 2012). The interpretation of bodily signs is very much influenced by previous experiences, and it does not necessarily reflect the objectively available sensory information (Brown, 2004; Edwards et al., 2012; van den Bergh, Brown, Petersen, & Witthöft, 2017; van den Bergh, Witthöft, et al., 2017), as it is clear in the case of somatosensory amplification (Köteles & Witthöft, 2017; Mailloux & Brener, 2002).

The main limitation of the study roots in the problems of conceptualizing interoception and body awareness. The wide variety of interoceptive channels and questionnaires narrows down the possibility of generalization. Interoceptive accuracy can be investigated using various different interoceptive channels, for example respiration (Daubenmier et al., 2013), blood pressure (Greenstadt et al., 1986) and gastric contraction (Herbert et al., 2012; Whitehead & Drescher, 1980). There are exceptions (Herbert et al., 2012), but the majority of the studies shows that the results using different methods and channels are independent of each other (Ferentzi et al., 2017; Garfinkel et al., 2016; Harver et al., 1993; Pennebaker & Hoover, 1984; Steptoe & Noll, 1997; Vaitl, 1996; Werner et al., 2009). Findings from questionnaire studies measuring self-reported facets of interoception, on the other hand, are usually generalized across different interoceptive channels, and the results are also highly influenced by subjective factors. Moreover, the difference between interoceptive awareness and body awareness is not clearly presented through the literature and the items of the questionnaires, as discussed above. Considering the technical part, the mental tracking task of Schandry (Schandry, 1981) has been widely criticized. One of the main concerns is that the results of the heartbeat counting task is very much influenced by other factors than the true awareness of the heartbeats (Ring et al., 2015). For example expectations, beliefs, preconceptions and knowledge about heart rate (Pennebaker & Epstein, 1983; Phillips, Jones, Rieger, & Snell, 1999; Ring & Brener, 1996) might be significant confounding factors. On the other hand, as other authors pointed out (Ainley, Apps, Fotopoulou, & Tsakiris, 2016), extensive empirical evidence connect heartbeat perception ability to various measured variables, for example reviews support its prevalence in anxiety, anxiety disorders and panic disorders (Domschke et al., 2010; Van der Does et al., 2000). Even if the results partly represent some kind of distortion of perception or judgment that influences the results of the Schandry-task, nevertheless it is still informative that the measured phenomenon is a relatively stable characteristic. This stability is also supported by studies measuring heartbeat evoked potential (HEP) (Schandry, Sparrer, & Weitkunat, 1986); the altered amplitude of HEP mirrors heartbeat perception scores (Pollatos & Schandry, 2004; Terhaar, Viola, Bär, & Debener, 2012).

In this study, we used a stricter instruction during the heartbeat perception task, as participants were not allowed to guess, unlike in other studies (Pollatos & Schandry, 2004). This instruction decreased the probability of the influence of an educated guess regarding heartrate; on the other hand, this might be the cause of the relatively low heartbeat perception scores. It is worth to note, however, that there is no information whether participants followed the instruction. Guessing the heartbeat decreases greatly the reliability of the test. There are some new variations of the heartbeat perception method to measure IAc that eliminate some difficulties of the original version (Sedeño et al., 2014; Yoris et al., 2015). The application of these tasks might lead to different results.

The self-reported body awareness and the objectively measured interoceptive accuracy are independent, and temporally stable characteristics.

3. What makes sense in our body? Personality and sensory correlates of body awareness and somatosensory amplification (STUDY 2)[4]

3.1. Introduction

Proneness to focus on information originating from within the body and monitor body processes has received considerable attention in the last decades. Initially, this characteristic was investigated with regard to pathological conditions. For example, hypochondriasis or health anxiety, somatization, and alexithymia were all found to be connected to somatosensory amplification (SSA), the tendency to experience somatic sensation as intense, noxious, and disturbing (Barsky, 1992; Barsky, Wyshak, & Klerman, 1990; Duddu, Isaac, & Chaturvedi, 2006; Krautwurst et al., 2014; Wise & Mann, 1994; Witthöft & Hiller, 2010). Somatosensory amplification is thought to comprise a hypervigilance toward bodily sensations, an increased focus on weak and infrequent sensations, and a catastrophizing interpretation of these sensations, e.g. as symptoms of a disease (Barsky et al., 1990). Later, a distinction between evaluative (typically negative, as in the case of SSA) and non-evaluative (neutral) focusing style was proposed (Shields et al., 1989). Possible benefits of the latter style, often referred to as body awareness (BA), were emphasized (Daubenmier, 2005; N. A. S. Farb et al., 2015; Impett, Daubenmier, & Hirschman, 2006; Mehling et al., 2009). BA and SSA, which are considered trait like characteristics, showing considerable inter-individual variability, are measured using self-report instruments (questionnaires). SSA is usually assessed using the Somatosensory Amplification Scale (SSAS), while a number of instruments were developed for the measurement of BA (e.g. Private Body Consciousness Scale, Body Awareness Questionnaire) (Mehling et al., 2009).

Although the temporal stability of various aspects of body awareness and somatosensory amplification is well established (Barsky et al., 1990; Köteles & Simor, 2013; Miller et al., 1981; Shields et al., 1989), the connection between facets of BA and

4 The present chapter is the exact copy of the following paper: Ferentzi, E., Köteles, F., Csala, B., Drew, R., Tihanyi, B. T., Pulay-Kottlár, G., & Doering, B. K. (2017). What makes sense in our body? Personality and sensory correlates of body awareness and somatosensory amplification. *Personality and Individual Differences*, *104*, 75–81. https://doi.org/10.1016/j.paid.2016.07.034

SSA and major dimensions of personality has yet to be clarified. From a theoretical point of view, both constructs are related, by definition, to introspection and self-observation, which are often mentioned as fundamental characteristics of introversion (Barsky et al., 1990; Miller et al., 1981). Similarly, the negative affect and anxiety (both belong to the personality dimension of neuroticism) incorporated into the definition of SSA (Barsky, 1979; Barsky et al., 1990).

Concerning empirical evidence, somatosensory amplification was associated with indicators of negative affect and neuroticism/emotional instability in several studies (Aronson, Barrett, & Quigley, 2001; Barsky & Wyshak, 1990; Ferguson, 2000; Lee, Watson, & Frey Law, 2013; Lee, Watson, & Frey-Law, 2010); however, no connection between SSA and any of the five major factors of personality were reported in one study (M. P. Jones, Schettler, Olden, & Crowell, 2004). Beyond neuroticism, a weak negative correlation between SSA and surgency/extraversion was found in one study (Ferguson, 2000); while SSA was connected to neuroticism and conscientiousness after controlling for alexithymia in another (Wise & Mann, 1994). Empirical findings on the connections between personality dimensions and BA are even more scarce. One study found no differences among meditators, dancers and a control group regarding the Big Five dimensions, although the levels of BA were significantly different (Sze, Gyurak, Yuan, & Levenson, 2010). Conversely, both self-reflectiveness and internal state awareness were associated with openness; while the latter was related to conscientiousness as well (Trapnell & Campbell, 1999). Additionally, considering its non-evaluative quality, BA should be independent of neuroticism/emotional stability or negative affect, as previously reported by several authors (Köteles et al., 2012; Shields et al., 1989; Tolnai, Szabó, & Köteles, 2013). Although a connection with introversion appears to be plausible (Fenigstein, Scheier, & Buss, 1975), this hypothesis has not been tested empirically to date.

The relationship between SSA and BA is worthy of further elaboration. Although SSA was originally defined and discussed as comprising a heightened body focus (Barsky, 1979; Barsky et al., 1988), this connection was only evidenced decades later (Fabbri, Kapur, Wells, & Creed, 2001; Köteles & Doering, 2016). Body focus is often assumed to directly rely on, and process, sensory (interoceptive) information. According to empirical findings, however, neither SSA nor BA (as assessed by self-report instruments) are characterized by heightened sensitivity to interoceptive signals (usually measured using a heartbeat detection task) (Ainley & Tsakiris, 2013; Aronson et al., 2001; Barsky et al., 1995; Dunn, Dalgleish, Ogilvie, & Lawrence, 2007; Emanuelsen et al., 2015; Mailloux & Brener, 2002; Marcus, Gurley, Marchi, & Bauer, 2007). Recently, interoceptive accuracy and body focus are regarded as different constructs: the former is connected to the accuracy of detection of sensory information, while the latter refers to a conscious representation of the body (i.e., being aware of perceived changes) (Calì et al., 2015; Ceunen et al., 2013; N. A. S. Farb et al., 2015; Garfinkel, Seth, et al., 2015; Ginzburg, Tsur, Barak-Nahum, & Defrin, 2014), which can be affected by various biases and memories of past sensations (Brown, 2004). For example, somatosensory amplification, which actually could be considered body awareness accompanied by negative affect (Köteles & Doering, 2016), was associated with diminished interoceptive accuracy in several studies (Barsky et al., 1995; Barsky, Cleary, Brener, & Ruskin, 1993; Mailloux & Brener, 2002). In conclusion, SSA has been conceptualized as a specific cognitive bias which negatively impacts the accurate perception and interpretation of body signals (Mailloux & Brener, 2002).

A more differentiated distinction between various interoceptive signals may help to clarify the relationships between interoception, BA, and SSA, respectively. Interoception (and visceroception in particular) is characterized by relatively high perception thresholds; therefore, at least under healthy circumstances, we are barely able to sense information originating from the viscera (Ádám, 1998). This phenomenon can be explained by the limited capacity of our attentional and information processing systems (Pennebaker, 1982; Pennebaker & Lightner, 1980). As external stimuli are generally more important for everyday functioning (and necessary for survival from an evolutionary perspective), interoceptive input reaches consciousness only when the information transmitted is crucially important for the organism (Ádám, 1998). For example, the (normo)tension of single muscle fibers, vestibular information for maintaining balance, and resting heart rate are processed at lower levels of the central nervous system (i.e., in the brainstem). These signals contribute to automatic homeostatic and motor regulation processes, and therefore they do not need to reach conscious awareness. Conversely, pathological conditions, injuries, and even the possibility of tissue damage, represent information that can be crucial to survival; thus, pain has evolved as a specific signal that is able to easily reach consciousness, catch attention, and initiate the necessary behavioral changes (Macdonald & Leary, 2005; Melzack & Wall, 1965; Wall, 2000).

As (1) pain-related information is present in conscious awareness, and (2) has a strong affective (i.e., aversive) component (Price, 1999), it might be influenced by cognitive biases. In line with these theoretical considerations, SSA was found to be connected to many pain-related conditions. For example, myofascial pain (Raphael, Marbach, & Gallagher, 2000), rheumatoid arthritis (Barsky et al., 1999), joint hypermobility syndrome (Baeza-Velasco, Gély-Nargeot, Bulbena Vilarrasa, & Bravo, 2011; Baeza-Velasco, Gely-Nargeot, Vilarrasa, Fenetrier, & Bravo, 2011), non-ischaemic/non-cardiac chest pain (Nakao, Tamiya, & Yano, 2005; Schroeder et al., 2012; Schroeder, Gerlach, Achenbach, & Martin, 2015; Zincir et al., 2014), headache (Barke, Gaßmann, & Kröner-Herwig, 2014), migraine (Yavuz, Aydinlar, Dikmen, & Incesu, 2013), and fibromyalgia (Duruk, Sertel Berk, & Ketenci, 2015) have all been associated with SSA in the literature. Additionally, one study found that SSA was related to pain perception in healthy individuals (Lee et al., 2010). However, our understanding concerning the connection between BA and pain is less clear. On the one hand, less focus on somatic pain has reduced suffering (Johnson, 2005); while on the other hand, greater focus on the sensory component of pain has benefited people with chronic low back pain (Burns, 2006).

Similarly to pain, sensitivity to bitter taste may have evolved as a defense (i.e., to facilitate avoidance of food that can be dangerous) and is characterized by a low perceptual threshold and a strong negative affective component (Glendinning, 1994; Li, Pakstis, Kidd, & Kidd, 2011; Shi, Zhang, Yang, & Zhang, 2003). Although the gustatory system is regarded as an exteroceptive sensory modality, it is represented together with interoceptive information in the nervous system (Avery et al., 2015). Based on these characteristics, it is plausible to assume that sensitivity to the bitter taste can also be connected to SSA and BA.

Vestibular information, although considered interoceptive, has a different quality than other sensory modalities (e.g. pain, taste). Studies found that vestibular signals influence the perception of somatosensory information and multisensory functions that may contribute to body awareness (Ferrè, Berlot, & Haggard, 2015; Ferrè, Vagnoni, &

Haggard, 2013). Furthermore, a recent review emphasizes the contribution of the cortical network of the vestibular system to body awareness and self-awareness (Lopez, 2016). These findings illustrate that conscious awareness is not required for vestibular input to play a modulating role in the perception of other signals, and general body awareness.

In summary, the current study was designed to shed more light on the personality and the sensory background of body awareness and somatosensory amplification. Regarding personality dimensions, based on the aforementioned empirical results and theoretical considerations, we expect (Hypothesis 1) a positive connection between introversion and both SSA and BA; (H2) a positive connection between neuroticism and SSA; and (H3) no connection between neuroticism and BA. We also intended to explore associations between the indicators of body focus and the remaining three Big Five dimensions. Concerning sensory modalities, it was expected that (H4) pain threshold and tolerance, as well as (H5) perceived intensity and unpleasantness of a bitter solution, would be positively connected to SSA and BA; while (H6) heartbeat detection ability and (H7) balancing ability would not.

3.2. Materials and methods

Participants

This was a cross-sectional study, involving both questionnaires and sensory measurements. Questionnaires were completed by 212 undergraduate university students (age: 22.2±2.76 years, 54.7% female). From this first sample, 118 students ($N = 118$, 21.2±1.39 years, 55.9% female) also participated in the sensory measurements (see below). The size of this latter subsample was determined by an *a priori* effect size calculation for a multiple linear regression analysis with six variables representing the sensory measurements. Parameters of the calculation were medium effect size ($ES = 0.15$), $\alpha = 0.05$, $1-\beta = 0.80$, and the calculation was carried out using the G*Power v3.1.9.2. software (Faul, Erdfelder, Lang, & Buchner, 2007). Participation was voluntary and subjects received no reward for their participation. Questionnaires were completed on-line before the first sensory measurement. The four sensory measurements were carried out by expert researchers on separate days, in a random order. No data with respect to self-report questionnaires and the balancing task (see below) was missing. Pain-related data was missing for one participant, heartbeat detection performance was missing for six individuals, and bitterness sensitivity was not measured for two individuals. The research was approved by the Research Ethical Board of the Faculty of Pedagogy and Psychology, XXX University, Hungary. All participants signed an informed consent before the study.

Questionnaires

The *Somatosensory Amplification Scale* (SSAS) (Barsky et al., 1990) was used to assess the tendency to experience a somatic sensation as intense, noxious, and disturbing. The SSAS consists of 10 self-rated statements that are estimated on a 5-point Likert-scale, with higher scores indicating higher levels of amplification tendency. The Hungarian version has proven to be valid and psychometrically sound with a Cronbach's alpha in the range of .70 to .77 (Köteles et al., 2009). Its internal consistency was .70 in the present study, as it was in the original study (Barsky et al., 1990).

Body Awareness Questionnaire (BAQ) (Shields et al., 1989) measures one's beliefs about one´s sensitivity to normal non-emotive bodily processes, and the ability to anticipate bodily reactions. The scale consists of eighteen items which are rated on a 7-point Likert-scale, with higher scores representing higher levels of body awareness. Its internal consistency in the original study was .82 (Shields et al., 1989). The Hungarian version showed good validity and reliability in past studies (Emanuelsen et al., 2015; Köteles, 2014), with a Cronbach's alpha in the range of .81-.88. In the present study, the internal consistency of the scale was .84.

The *Big Five Inventory* (BFI) (Benet-Martínez & John, 1998; John, Donahue, & Kentle, 1991) measures the five broad dimensions (i.e., extraversion, agreeableness, conscientiousness, emotional stability, openness to experience) of personality. The Hungarian version of the scale showes good psychometric properties, with a Cronbach's alpha coefficients of .79 for extraversion, .72 for agreeableness, .82 for conscientiousness, .82 for emotional stability, and .78 for openness to experience (Rózsa, Kő, Surányi, & Orosz, 2016). The 44 items of the inventory are rated on a 5-point Likert scale. In the present study, Cronbach's alpha coefficients were .75 for extraversion, .79 for agreeableness, .82 for conscientiousness, .77 for emotional stability, and .79 for openness to experience.

Sensory measurements

Pain

Experimentally induced ischemic pain of the skeletal muscles was used as an index of sensitivity to pain. Pain in the forearm was evoked using a modified version of the tourniquet technique described by Amanzio and Benedetti (Amanzio & Benedetti, 1999). Subjects reclined on a bed, with their right forearm extended vertically, while venous blood was drained from the arm using an Esmarch bandage. A sphygmomanometer was placed around the upper arm, and inflated to 250 mmHg, then participants were asked to squeeze a hand spring exerciser 12 times. Each squeeze lasted 2 sec, and was followed by a 2 sec rest. Resistance of the exerciser was set to 0.3 x bodyweight (kg). Time measurement started after the last squeeze, and time of pain threshold (i.e., when the sensation was first described as pain) and pain tolerance (i. e., when the pain became unbearable) were registered in seconds.

Balancing

Balancing ability was assessed using two one-minute balancing tasks. Participants were asked to stand on their right leg, then left leg, with closed eyes and the average number of step downs was calculated (lower values indicate higher reliance on vestibular and proprioceptive stimuli).

Heartbeat perception

Heartbeat detection ability was used to characterize interoceptive sensitivity (IS). Perception of heartbeats was measured using a modified version of the Mental Tracking Method (MTM) (Emanuelsen et al., 2015; Schandry, 1981). Following a 15-second test trial, participants were asked to count their heartbeats during intervals of 30 sec, 45 sec, and 100 sec, presented in random order, with a 10 second rest between them. At the same time, the experimenter counted the participants' actual heartbeats using a Polar watch (model RS-400) with chest strap. All subjects were asked to remain in a comfortable seated position and breathe at a regular pace during the tracking intervals. Accuracy of heartbeat detection in a given session was calculated using the following formula: 1- | (recorded heartbeats - counted heartbeats)/recorded heartbeats |

Interoceptive sensitivity (IS) was calculated as the mean score of three (30s, 45s, 100s) heartbeat perception intervals, with higher scores indicating higher levels of accuracy.

Bitterness sensitivity

Participants were asked to taste a standard extract of a widely used herbal digestive and aperitif (*Centaurii herba*). The extract was prepared by steeping 1 g of the drug in 1 l of hot water for 5 minutes. Bitterness and unpleasantness were rated on a 10 cm visual analogue scale, where the subjects indicated the strength of their sensations by marking a position between two endpoints. Higher values indicate higher levels of perceived bitterness and unpleasantness, respectively.

Calculation

Data was analyzed using the SPSS v20 software. As several variables showed deviations from normal distribution (Shapiro-Wilk tests), connections among indicators of somatic focus and sensory related variables, and correlations between indicators of somatic focus and the big five personality dimensions were estimated using Spearman correlations. Variables that significantly correlated with the SSAS score were also subjected to a hierarchical multiple linear regression analysis. Variables were entered using the STEPWISE method in three steps: (Step 1) sensory variables (pain threshold, pain tolerance, bitter unpleasantness), (Step 2) broad personality dimensions (emotional stability, extraversion), and (Step 3) body awareness.

3.3. Results

Descriptive statistics are presented in Table 6.

Table 6. Descriptive statistics of the measured variables

	N	Range	Mean±Std. Deviation	Skewness	Kurtosis
BAQ	212	37-119	85.84±14.208	-0.515	0.604
SSAS	212	14-45	30.18±5.861	-0.341	0.147
Extraversion	212	16-39	28.717±4.925	-0.018	-0.487
Agreeableness	212	19-44	33.255±5.132	-0.246	-0.531
Conscientiousness	212	19-43	31.500±5.067	-0.084	-0.474
Emotional Stability	212	12-39	26.094±5.199	0.150	-0.237
Openness to experience	212	20-47	35.486±5.652	-0.126	-0.468
Pain threshold (sec)	117	4-900	368.99±312.444	0.567	-0.999
Pain tolerance (sec)	117	80-1200	801.96±311.158	-0.545	-0.580
Balancing	118	0-14.5	1.97±2.864	2.252	5.596
Interoceptive sensitivity	112	0.060-1.127	0.66±0.202	-0.403	0.105
Bitterness intensity	116	0-10	4.81±3.269	0.045	-10.290
Bitterness unpleasantness	116	0-10	4.24±3.309	0.243	-10.294

According to the results of the correlation analysis, somatosensory amplification showed weak to medium level connections with pain threshold, pain tolerance, perceived unpleasantness of the bitter taste, and body awareness (for details, see Table 7). No significant correlation with heartbeat detection ability, perceived intensity of the bitter taste, and reliance on the vestibular system in the balancing task was found. Body awareness (as assessed by the BAQ) was not connected to any sensory variable. Moreover, no significant correlations among variables representing different sensory modalities were found.

Concerning connections with the broad dimensions of personality, body awareness was weakly related to conscientiousness ($\rho = .25$, $p < .001$) and openness to experience ($\rho = .19$, $p = .005$), whereas somatosensory amplification was reversely related to extraversion ($\rho = -.15$, $p = .031$) and emotional stability ($\rho = -.21$, $p = .002$). No further significant correlations were found.

Table 7. Spearman correlation coefficients and 95% confidence intervals among measures of somatic focus and sensory measurements

	SSAS	IS	Pain threshold	Pain tolerance	Bitterness	Bitter unpleasant-ness	Balancing
BAQ	.26 (.064;.432)	-.13 (-.317; .085)	.02 (-.173; .202)	.14 (-.038;.315)	-.04 (-.241;.167)	-.03 (-.226;.164)	.01 (-.185;.202)
SSAS		-.02 (-.223; .177)	-.33 (-.494; -.133)	-.24 (-.423;-.051)	.18 (-.042;.371)	.20 (-.009;.391)	-.03 (.182;.137)
IS			.13 (-.078; .307)	.11 (-.09;.294)	.03 (-.162;.217)	.00 (-.203;.202)	.14 (-.056;.330)
Pain threshold				.71 (.585;.811)	-.11 (-.281;.065)	-.10 (-.286;.066)	.12 (-.051;.312)
Pain tolerance					-.19 (-.364;-.010)	-.18 (-.352;-.009)	.07 (-.111;.263)
Bitterness						.91 (.854;.943)	.05 (-.151;.224)
Bitter unpleasant-ness							.08 (-.107;.260)

Note: BAQ: Body Awareness Questionnaire; SSAS: Somatosensory Amplification Scale; IS: Interoceptive Sensitivity (heartbeat detection task).

Table 8. Results of the multiple linear regression analysis with SSAS score as dependent variable

	Step 1 $R^2 = .074$ F(1,113) = 8.992 p = .003			**Step 2** $R^2 = .111$ F(2,112) = 7.017 p = .013			**Step 3** $R^2 = .230$ F(3,111) = 11.042 p < .001		
	standar-dized β	**t**	**p**	**standar-dized β**	**t**	**p**	**standar-dized β**	**t**	**p**
pain threshold	-.271	-2.999	.003	-.280	-3.142	.002	-.310	-3.702	< .001
extraversion	-	-	-	-.194	-2.178	.031	-.229	-2.728	.007
body awareness							.347	4.133	< .001

The first equation of the multiple linear regression analysis explained 7.4% of the total variance of the SSAS score, the only significant predictor variable in the equation was pain threshold (for details, see Table 8). After entering the two personality related variables (Step 2), the equation explained 11.1% of the variance through two predictor variables: pain threshold and extraversion. The final equation ($R^2 = 0.230$, $p < .001$) included pain threshold, extraversion, and body awareness.

3.4. Discussion

In a cross-sectional study with the participation of young healthy individuals, (Hypothesis 1) introversion was connected to somatosensory amplification (SSA); surprisingly, it was not associated with body awareness (BA). As expected, neuroticism was (H2) related to SSA, but (H3) not to BA. Concerning the different sensory modalities, (H4) pain threshold and tolerance were connected to SSA, but not to BA. The same tendency was found (H5) in the case of perceived unpleasantness of bitter taste, but not for perceived intensity of the sensation. As expected, (H6) heartbeat detection ability and (H7) balancing ability were not connected to either SSA and BA. In further exploration, BA showed weak connections to openness and conscientiousness. Additionally, SSA and BA were affiliated.

Interoception is often defined in broad terms, encompassing all forms of sensory information originating from within the body, and implicating an interoceptive center in the insular cortex (Cameron, 2001, 2002; Craig, 2002, 2008). Some studies support the notion that interoceptive ability is generalized across modalities (Herbert et al., 2012), while others found specific sensitivity levels with respect to different bodily sensations (Steptoe & Noll, 1997; Werner et al., 2009). Our results support the latter findings, namely that the ability to detect bodily signals is not generalized across various sensory modalities.

Based almost exclusively on heartbeat detection related findings, it has been accepted in the literature that the constructs of health anxiety and SSA are not connected to higher levels of interoceptive accuracy (Marcus et al., 2007; Nakao, Barsky, Nishikitani, Yano, & Murata, 2007). However, if performance on the heartbeat detection task is not a generalizable estimation of interoceptive accuracy, then this view can no longer be taken for granted. Moreover, when exploring sensory channels with a low perceptual threshold, conscious perception is rarely an issue. In the current study, SSA was related only to sensory modalities which could represent a threat to the organism (i.e., that are subject to automatic evaluation); therefore, these sensations easily reach consciousness. This finding is in line with the recent conceptualization of SSA: (1) it is connected to the conscious representation of the body but not to lower sensory thresholds in general, and (2) it involves negative evaluation (sometimes referred to as a bias) (Köteles & Doering, 2016; Mailloux & Brener, 2002; Nakao et al., 2007). Similarly to health anxiety (Barsky et al., 1990; Köteles & Simor, 2013), weak to moderate levels of SSA can be considered evolutionarily adaptive, as they help the organism to avoid risky behaviors and situations by enhancing the aversiveness of typically threatening stimuli. The fact that BA, providing an evaluation-free representation of the body, was not related to any interoceptive modalities is in accordance with previous findings (Ainley & Tsakiris, 2013; Dunn et al., 2007; Emanuelsen et al., 2015), and also with an evolutionary approach.

Our findings indicate an association between SSA and conscious interoceptive signals with a threatening quality. One possible explanation for this association suggests that SSA is merely an indicator of negative affect (Aronson et al., 2001); however, considering that the connection between SSA and emotional stability was weak in the current study, and SSA was also related to body awareness, this explanation seems less plausible. Moreover, in another study investigating SSA, tactile sensitivity and anxiety simultaneously, the relationship between SSA and tactile perception remained significant, even when controlling for trait anxiety (Brown, Poliakoff, & Kirkman, 2007).

Contrary to our expectations, BA was not related to introversion (defined as the opposite end of extraversion on the extraversion-introversion factor of Big Five); however, our results are in accordance with earlier findings on its connection to conscientiousness and openness to experience (Trapnell & Campbell, 1999). People with higher levels of openness were described as curious (Peabody & Goldberg, 1989), and characterized receptiveness to different novel experiences (McCrae & Costa, 1983). A recent review outlines two main aspects of openness, namely intellect and experiencing, and describes the latter as curiosity (interest in exploring and understanding novel information) and openness to sensation (tendency to savor a variety of sensory experiences) (Connelly, Ones, & Chernyshenko, 2014). Conscientiousness is the tendency to inhibit and control behavior on the one hand, and to organize and direct it on the other (MacCann, Duckworth, & Roberts, 2009; McCrae & John, 1992). In a similar manner to environmental stimuli, body related information can be novel and interesting, catching the attention of people who are open to sensation, and satisfying the curiosity of individuals with higher levels of openness. Concerning conscientiousness, a more regular and systematic process of introspection and self-description can result in a more elaborated representation of the body.

Personality correlates of SSA (emotional lability and introversion) and BA (conscientiousness and openness to experience) are in accordance with a number of previous findings (Aronson et al., 2001; Ferguson, 2000; Lee et al., 2013, 2010; Trapnell & Campbell, 1999) and seem plausible from a theoretical point of view. However, as correlations among constructs were low to medium level only, the connection with the Big Five factors should not be overemphasized, and the relevance of further personality constructs may be worthy of consideration (see for example: Fassino, Pierò, Gramaglia, & Abbate-Daga, 2004; Lyons & Hughes, 2015. The reported connection between SSAS and BA also replicates previous findings (Fabbri et al., 2001; Köteles & Doering, 2016); however, the present study used a different questionnaire (BAQ instead of the Private Body Consciousness Scale) which exhibited higher internal consistency.

Conclusion

We interpret the relationship between higher SSA and the associated lower pain threshold, lower pain tolerance and greater perceived unpleasantness of a bitter taste as being the result of the respective interoceptive signals reaching consciousness and being negatively evaluated. This hypothesis may help to explain why higher SSA is also associated with an increased report of side effects after drug intake (Barsky et al., 1999; Davis, Ralevski, Kennedy, & Neitzert, 1995; Doering et al., 2015; Doering, Szécsi, Bárdos, & Köteles, 2016; Köteles & Bárdos, 2011; Wendt et al., 2014). If we assume that many side effects originate from interoceptive stimuli that reach consciousness and are perceived as threatening, it would concur with the present experimental data. Since we cannot influence whether a stimulus reaches consciousness, changing the interpretation of the stimuli could be a potential means by which to minimize side effects (Barsky, Saintfort, Rogers, & Borus, 2002). Providing realistic but positive information about side effects, and focusing on a coping-oriented perspective for side effect management, may thus be especially important for individuals with higher levels of SSA (Doering & Rief, 2012). Future studies are needed to clarify whether this holds true for both drug-specific side effects and nonspecific side effects (i.e., nocebo effects).

The current study is not without limitation. The inclusion of more interoceptive modalities and objective methods of data collection would provide a stronger foundation for our conclusions. In addition, the healthy sample of university students prevents generalization of the results to a wider population, or clinical subgroups. In future studies, a longitudinal design would allow for investigation of the stability and trait-like qualities of the measured body-related variables.

4. Multichannel investigation of interoception: Sensitivity is not a generalizable feature (STUDY 3)[5]

4.1. Introduction

Interoception, the perception of the state of the body (Ceunen et al., 2016) is a multimodal construct that includes several physiological channels. Beyond modality-specific information, integrated interoceptive information provides the sense of the physiological condition of the entire body (Craig, 2002, 2003b), the basis for subjective feeling states (Craig, 2002), and the sense of self (Craig, 2015; Damasio, 1999). Interoception originally only referred to visceroception (Ceunen et al., 2016), but recent neuroanatomical findings support the notion that a wide variety of bodily information becomes integrated at the level of the insula, contributing to the maintenance of homeostasis, and providing the subjective *'Gemeingefühl'* or common sensation, i.e. how we feel in our body (Craig, 2015). These findings are in line with a more inclusive conceptualization of interoception (Ceunen et al., 2016).

There are two distinct neural pathways of interoceptive information (Craig, 2015). One ascends from the skin, muscles and joints through the medial lemniscus or the analogue cranial nerves to the thalamus, and ends in the somatosensory cortex. It carries proprioceptive and mechanical (tactile) information. The other pathway relays the primary visceral information upward to another region of the thalamus using the spinothalamic tract; then it reaches the insula (Craig, 2009). This tract is responsible for a wide variety of sensations, such as pain, temperature, affective touch and visceral sensation (Craig, 2015). The information provided by these two pathways (along with the input from the gustatory system (Avery et al., 2015) is integrated at multiple levels, among which the medial and the anterior insular cortex play the primary role (Craig, 2015). As a consequence, the anterior part of the insular cortex can be activated by a variety of stimuli, such as taste, thirst, sensual touch, itch, sexual arousal, warmth, and

5 The present chapter is the exact copy of the following paper: Ferentzi, E., Bogdány, T., Szabolcs, Z., Csala, B., Horváth, Á., & Köteles, F. (2018). Multichannel investigation of interoception: Sensitivity is not a generalizable feature. *Frontiers in Human Neuroscience*, *12*. https://doi.org/10.3389/fnhum.2018.00223

distension of the stomach or rectum (Craig, 2004, 2009). For example, the heightened activity in the right (non-dominant) anterior insular/opercular cortex, as measured with functional MRI, predicted the performance level in the heartbeat detection task (Critchley et al., 2004).

Despite the multiple integrations of the interoceptive information in the central nervous system, it is an open question whether we can talk about general interoceptive ability, and how this could be described and understood. It was proposed that great intra- and interindividual variability exist regarding the accuracy of different interoceptive channels (Vaitl, 1996). For example, someone with a good performance in cardiac perception is not necessarily sensitive to other bodily cues, such as signals originating in the gastrointestinal or respiratory system (Vaitl, 1996). Until recently, both the number of empirical studies investigating multiple interoceptive channels simultaneously, and the number of the investigated modalities have been limited.

Most of the empirical results support the supposition of Vaitl (1996), except two studies that compared the cardiac and the gastrointestinal system. An early study found a medium level correlation between the accuracy of detection of heartbeats and stomach contractions (Whitehead & Drescher, 1980). The same level of association between cardiac and gastric perception was demonstrated using a different methodology, i.e. the heartbeat tracking and water load test paradigms (Herbert et al., 2012). Another study investigated three channels, and found significant moderate associations between the perception of skin conductance level (assessed by the sensation of dry versus sweaty hands) and the two other measured variables, namely the perception of heart rate and respiratory resistance. However, the latter two did not correlate with each other (Steptoe & Noll, 1997). It is important to emphasize that the effect size of the aforementioned associations is in the moderate domain, explaining only 13 to 25% of the total variance (Herbert et al., 2012; Steptoe & Noll, 1997; Whitehead & Drescher, 1980).

The majority of empirical studies did not find associations between the investigated modalities. A study encompassing heartbeat discrimination and respiratory resistance tasks applying signal detection theory found that neither perceptual accuracy nor response bias were related among the tasks (Harver et al., 1993). A recent study reported similar results (Garfinkel et al., 2016). A comparison between the threshold and tolerance for heat pain and the results of heartbeat tracking task found no association between the sensation of pain and cardiac activity (Werner et al., 2009). Our recent study investigated four interoceptive channels, namely heartbeat perception with the tracking task, pain threshold and tolerance in induced ischemic pain, bitterness sensitivity and balancing ability (Ferentzi et al., 2017). Again, no correlations were found between any of the investigated sensory channels. Another study that reported preliminary results revealed an association between cardiac and gastric accuracy, but no connection between these variables and respiratory sensitivity was found (Garfinkel, Manassei, Engels, Gould, & Critchley, 2017). It is important to note, however, that the interpretation of the results of this study is problematic due to the small sample size and lack of methodological information.

Another way to define the general interoceptive ability is not to presume that the sensitivity and accuracy of different interoceptive channels are more or less similar in magnitude. Instead, the combination or integration of those interoceptive channels may provide some kind of general interoceptive ability. The fact that information originating in various interoceptive channels becomes more and more integrated in higher levels of central processing, and also the concept that this integration has a homeostatic function in Primates (i.e. the assessment of the general state of the body; Craig, 2015) support this assumption. Empirical testing of this hypothesis, however, is difficult, as the general feeling about the body is measurable only via self-report. Interoceptive awareness (Ceunen et al., 2013) or sensibility (Garfinkel & Critchley, 2013; Garfinkel, Seth, et al., 2015), defined as self-reported interoceptive ability, might be biased in different ways. Questionnaires, usually assessing a variety of interoceptive channels, are meant to measure the general perceived interoceptive ability, but they are influenced heavily by memory and subjective interpretation. Additionally, the interoceptive ability level assessed with questionnaires is not associated with the level investigated with behavioral tasks (Garfinkel, Seth, et al., 2015).

The available information concerning the relationships of the accuracy of various interoceptive channels is scarce and inconclusive. Although the contemporary broad conceptualization of interoception includes the lemniscus medialis pathway (proprioceptive and tactile information), the integration of these modalities with those transmitted by the spinothalamic tract has not been investigated systematically to date. Additionally, most studies with multichannel approach measured only a limited number of modalities.

The aim of the present study is to investigate whether information obtained from a single interoceptive modality can be generalized to other modalities. According to our hypothesis, there will be no considerable associations among various interoceptive channels, except of the association between heartbeat perception and gastric sensitivity.

4.2. Material and Method

Participants

For factor analysis, the primary statistical method applied in the current study, no formal a priori sample size calculation can be conducted. Taken into consideration the complexity of the study and the expected high drop-out rate, our pre-determined goal was achieving a variables-to-factors ratio of 10 (Everitt, 1975) after the exclusion of participants with missing data from more than 2 sensory modalities.

Undergraduate university students (N = 142, 54% male; age: 21.93±3.582) participated in the study. Individuals with missing data for more than two tasks out of the six were excluded (N = 24). In the final sample (N = 118, 53% male; age: 21.72±3.007), data was missing for 11 participants for the heartbeat perception task, 29 participants for the water load task, 20 participants for the bitterness task, 17 participants for the pain task, 5 participants for the proprioceptive tasks, and 8 individuals for the balancing task.

The study was carried out in accordance with the Declaration of Helsinki. The protocol was approved by the Research Ethical Board of the Faculty of Pedagogy and Psychology, ELTE Eötvös Loránd University, Budapest, Hungary. All subjects signed an informed consent form before the measurements.

Sensory measurements

We used six different sensory measurements in the present study. Compared to our previous investigation (Ferentzi et al., 2017), we implied two main modifications. First, the proprioceptive modality was also included. Second, we investigated one more 'classic' visceroceptive channel, namely gastric perception.

Heartbeat perception task

To assess the ability to perceive heartbeats, the slightly modified version of the tracking task of Schandry was conducted (Schandry, 1981), just like in our previous study (Ferentzi et al., 2017). Participants counted their heartbeats silently in a seated position through three time period (30 sec, 45 sec and 100 sec, in random order; after a 15 sec long trial). Accuracy of perception was calculated for each trial using the following formula: 1−|(recorded heartbeats−counted heartbeats)/recorded heartbeats|; which was followed by the calculation of the mean score. Higher scores refer to higher levels of accuracy. Participants were instructed to breathe regularly; they were not allowed to take their pulse or use other techniques that could help counting. They were encouraged to only count those heartbeats they were sure about, but also instructed to take into account weak sensations.

Water load test

Gastric perception ability was assessed by a non-invasive method, a modified version of the water load test (Boeckxstaens et al., 2001). The duration of the task was five minutes; participants drank the same amount of water (adjusted to their height in cm; e.g. 175 ml with a height of 175 cm) in every minute. After each dose, they rated the sensation of gastric fullness and gastric unpleasantness, using a 10 cm long visual analogue scale. The difference between the fifth and the first rating was calculated for both scales. Higher scores indicate higher sensitivity to gastric distension.

Bitterness sensitivity

Sensitivity to taste was measured using an extract that was prepared using a herbal *(Centaurii herba)* by steeping 1g of the dry plant in 1l hot water for 5 min. Participants were asked to taste the liquid and to rate how bitter (bitter intensity) and how unpleasant (bitter unpleasantness) it was, using a 10 cm long visual analogue scale; higher values indicated higher levels of subjective perceptions. The same method was used in our previous study (Ferentzi et al., 2017).

Pain

Pain threshold and tolerance were assessed using a modified version of the tourniquet technique (Amanzio & Benedetti, 1999), as we used in our previous study (Ferentzi et al., 2017). Subjects were in a lying position with their forearm extended vertically, while venous blood was drained from the arm with an Esmarch bandage; then sphygmomanometer placed around the upper arm was inflated to 300 mm Hg. Participants were asked to squeeze a hand grip 12 times; each squeeze lasted 2 s with 2 s rest in between. The resistance of the exerciser was set to 10 kg. The time of pain threshold (i.e., when the sensation was first described as pain) and pain tolerance (i.e., when the pain became unbearable) were registered in seconds, starting the time measurement after the last squeeze.

Proprioceptive task

The proprioceptive sensitivity of the elbow joint was investigated using the modified version of the device of Goble (2010). Participants were in a seated position with the elbow placed on a rotatable board at shoulder height, eyes closed. The first task was to reproduce the position of the same forearm by moving the elbow only (proprioception, one arm), while the second task was to replicate the position of the opposite forearm (proprioception, two arms). 10 trials were conducted per task, 5 per arm. The dominant and non-dominant arms were investigated in random order. Before each trial, the arm of the participants was always fully stretched. Positions to replicate were randomly presented between 30 and 150 degrees. Proprioceptive sensitivity was calculated by the mean of the difference between the target and reproduced position (in degree), using the results of the dominant arm only. Higher scores refer to lower levels of accuracy in proprioception.

Balancing

Processing of vestibular information was measured using a balancing task. Participants were asked to stand on one leg with closed eyes. Balance ability was assessed with the average time length (sec) of two trials of standing without step downs (max: 60 sec). With open eyes, all participants were able to stand on one leg for a minute, which indicates that physical skills did not limit their balancing performance. Higher scores refer to better balancing ability.

Protocol

All the participants were assessed in a five-week time period. Balance and proprioceptive abilities were assessed at the same occasion (in random order), just like the sensitivity to bitter taste and the water load test (always bitter taste first, not to modify bitter sensitivity by the feeling of fullness). Apart from that, sensory measurements occurred in random order at four different appointments.

Statistical analysis

Data were analyzed with the SPSS v21s software. Correlations among variables were estimated using Spearman correlation. Because of the large number (45) of correlation analyses, the accepted level of significance was set to 0.001 (Bonferroni correction). As data was appropriate for exploratory factor analysis (KMO = 0.389; Bartlett's test $p < 0.001$), Principal Component Analysis (PCA) and factor analysis with Maximum Likelihood (ML) extraction (both with Oblimin rotation) were chosen to explore combined associations of variables. The problem of missing data was addressed by using a matrix of expectation maximization correlations as input for the factor analyses (Weaver & Maxwell, 2014).

4.3. Results

Descriptive statistics and Spearman correlations are presented in Table 9. Only three significant ($p < 0.001$) correlations were found, consistently between the two indicators of same interoceptive channel, i.e. (1) pain ($\rho = 0.51$), (2) sensitivity to bitter taste ($\rho = 0.80$), and (3) gastric sensitivity ($\rho = 0.48$). All other correlations were non-significant at the adjusted level of p (0.001), and the absolute value of the majority of correlation coefficients (which is considered an effect size indicator) was in the 0.0-0.1 domain.

Table 9. Descriptive statistics (M±SD) of and Spearman correlations between the assessed variables

	pain th. (sec)	pain tol. (sec)	balance (sec)	bitter int.	bitter unpl.	gastric fullness	gastric discom-fort	heart-beat tracking	proprio-ception, one arm	proprio-ception, two arms
pain th. (sec)	**173.90 ±246.154**	.51*	.07	-.02	.01	.01	-.34	.07	-.03	-.10
pain tol. (sec)		**577.45 ±379.227**	-.05	-.07	-.03	-.08	-.18	.06	-.02	.10
balance (sec)			**24.13 ±18.612**	-.05	.00	-.01	-.13	-.01	-.06	-.10
bitter int.				**44.86 ±23.653**	.80*	-.13	.10	.05	-.20	.01
bitter unpl.					**37.31 ±26.084**	-.16	.10	.05	-.32	.05
gastric fullness						**34.25 ±22.974**	.48*	-.11	-.05	-.01
gastric discom-fort							**27.84 ±26.909**	-.26	-.12	-.01
heartbeat tracking								**.54 ±.272**	-.00	.06
proprio-ception, one arm									**5.63 ±2.686**	-.03
proprio-ception, two arms										**6.30 ±3.223**

Note: * = p < 0.001 (Bonferroni corrected level of significance)
pain th. = pain threshold; pain tol. = pain tolerance;
bitter int. = bitter intensity; bitter unpl. = bitter unpleasantness

Concerning the exploratory factor analysis, although communalities of three variables (the two proprioceptive variables and heartbeat tracking) were rather low (< 0.4), we decided to keep them. According to the results of an exploratory PCA, the first four components had an eigenvalue larger than 1 (2.027; 1.743; 1.562; 1.092). Considering the shape of the scree plot, a three factor solution appeared to be the best option (the first three factors explained 53.3 % of the total variance). Thus two other analyses with three factors using PCA and ML extraction method with oblimin rotation were conducted. Rotated structure matrices from the PCA and ML extraction are presented in Table 10 and 11. Correlations among extracted components were negligible (=<0.2) in all cases. No generalized underlying factor (i.e. a dimension with a disproportionally high eigenvalue and substantial loadings of various sensory modalities) was revealed.

Indicators related to bitter taste, distension of the stomach, and pain clearly loaded on different factors in both analyses. In the output of the PCA (Table 10), the one-arm proprioception task was reversely connected to the bitterness factor (Factor 1), while heartbeat tracking negatively loaded on the gastric factor (Factor 2). The two-arm proprioception task and balance did not load on any factor. Concerning the results of the ML extraction (Table 3), the one-arm proprioception task was reversely connected to the bitterness factor (Factor 3) again. The two-arm proprioception task, heartbeat tracking, and balance showed no considerable loading on any factor.

Table 10. Variables' loadings on the three factors yielded by Principal Component Analysis with Oblimin rotation (values larger than 0.3 are marked with bold)

	Factor 1	**Factor 2**	**Factor 3**
gastric fullness	-.090	**.856**	.162
gastric discomfort	.179	**.889**	-.094
heartbeat tracking	.154	**-.334**	.161
proprioception, one arm	**-.539**	-.164	-.238
proprioception, two arms	.085	-.033	.067
pain threshold	.110	-.041	**.840**
pain tolerance	.071	-.147	**.841**
balance	-.121	-.153	-.231
bitter intensity	**.893**	-.055	.014
bitter unpleasantness	**.910**	-.098	.044

Table 11. Variables' loadings on the three factors yielded by Maximum Likelihood extraction with Oblimin rotation (values larger than 0.3 are marked with bold)

	Factor 1	**Factor 2**	**Factor 3**
gastric fullness	.139	**.687**	-.067
gastric discomfort	-.151	**.960**	.225
heartbeat tracking	.011	-.242	.062
proprioception, one arm	-.035	-.087	**-.327**
proprioception, two arms	-.085	-.015	.029
pain threshold	**.990**	.056	.103
pain tolerance	**.521**	-.033	.006
balance	-.027	-.098	-.048
bitter intensity	-.111	-.021	**.862**
bitter unpleasantness	-.107	-.082	**.917**

4.4. Discussion

In an experimental study investigating the perception of a total of 10 variables belonging to 6 sensory channels (gastric perception, heartbeat perception, proprioception, pain, balance, and bitter taste), no between-channel connections and a general factor underlying interoceptive sensitivity were found. In the correlation and factor analyses, the different aspects of the same channel (i.e. fullness and discomfort of the stomach, intensity and unpleasantness of the bitter taste, and pain threshold and tolerance) consistently loaded on the same factor, supporting the notion, that modalities themselves provide congruent and strategic information. An exception was the proprioceptive test, where the two versions loaded on different factors. The two tasks might require different abilities: while utilization of short-term memory is needed for the one arm version, communication between the two hemispheres is required for the task conducted with two arms (Goble, 2010). This is the first study that investigates the relation of several distinct interoceptive channels including 'classic' visceroceptive modalities as well as channels that are related to proprioception or activated by possibly dangerous external stimuli.

The findings of previous studies comparing gastric sensitivity and heartbeat perception abilities (Herbert et al., 2012; Whitehead & Drescher, 1980) have not been replicated; on the contrary, PCA revealed a negative connection between the two channels. However, it is noteworthy that the methodology of both past studies differed from that of our study. Whitehead and Drescher (1980) used the perfused catheter method to assess stomach contractions, and the subjects had to decide whether the contractions coincided with an external light signal. Heartbeat detection accuracy was measured using a comparable method (Whitehead-paradigm), based on signal detection theory. The study of Herbert and colleagues (2012) interpreted the amount of consumed water as the measure of gastric sensitivity, as participants were instructed to drink until they reach the point of perceived fullness; while in the recent study the stimulation (i.e. the amount of water) was kept constant. Heartbeat perception ability was assessed using the Schandry mental tracking paradigm in the study of Herbert and colleagues as well as in the present study. In our research, however, perceived fullness and unpleasantness of the stomach might have been higher as a consequence of the forced drinking paradigm, particularly for those with higher sensitivity to negative sensations originating in the visceral region. A tendency to negative evaluation (i.e. negative affect) was reversely connected with heartbeat perception in past studies, and was explained as a negative cognitive bias that interferes with perceptual processes (Aamland, Malterud, & Werner, 2012; Aronson et al., 2001; Barsky et al., 1995; van den Bergh et al., 2004).

For the other non-expected negative correlation (i.e. the one-arm proprioceptive task was reversely connected with the bitterness factor in both analyses), we could not find any satisfying explanation. A distinct feature of the former task is that it requires short-term memory and cognitive effort, which can be negatively influenced by automatic evaluative processes. From this aspect, however, a negative connection with the pain factor would also be reasonable, both anatomically (the ischemic pain test was also conducted on the arm) and conceptually. To gain a better understanding of this finding, replication of the connection and an experimental study dedicated to the issue would be necessary.

General interoceptive ability

Overall, our findings strongly support the idea that interoceptive accuracy assessed with a single modality cannot be generalized across various channels. It is particularly striking that the widely used heartbeat tracking task showed no substantial connection with any of the interoceptive channels. In fact, even various aspects of cardioception (heartbeat detection, pulse rate perception, perception of arrhythmias) show no significant associations with each other (Barsky et al., 1993). To prevent confusion, our suggestion is to use the expression of 'heartbeat perception accuracy' instead of the misleading 'interoceptive accuracy', if only heartbeat perception is assessed. It is also important to note that the conclusion that interoceptive modalities are not independent from each other was drawn solely from the medium level association between cardiac and gastric perception. However, the connections between gastric sensation and other modalities were not investigated to date.

There are two possible conceptualizations of general interoceptive ability. One option is that it is manifested at the same level in every channel, i.e. the accuracy of different interoceptive modalities ought to be more or less the same, or at least correlate strongly for each individual. Findings of the present study, as well as those of previous studies with a medium effect size (Herbert et al., 2012; Steptoe & Noll, 1997; Whitehead & Drescher, 1980) do not support this possibility. Generalization across modalities or inferring from one modality to another does not appear to be a good practice in interoception related research or treatment. The other option is that general interoceptive ability cannot be measured by focusing on individual channels, because it represents the integration or combination of the accuracy levels of all the possible interoceptive modalities; thus, there is no strong association among modalities. This assumption is not contradictory to the findings available so far. Although empirical studies show that interoceptive information is integrated at various levels of the nervous system, it is an open question, how this integration is accessible by behavioral measurement methods (i.e. interoceptive tasks).

A recent model proposed by Smith and Lane (2015) describes three stages of the perception of body and emotions: 1) discrete body features, 2) whole-body patterns and 3) emotion concepts. By referring to other authors (Jackendoff, 1987; Prinz, 2004) they argue that stage 2 processes correspond to the phenomenological differences in the individual experiences, which are represented as a coherent whole-body pattern. Consequently, we do not typically experience discrete bodily cues that are linked to specific organs.

It is often assumed that interoceptive accuracy (Ceunen et al., 2013; Garfinkel, Seth, et al., 2015) or sensitivity, represent an objective measure (Critchley, Eccles, & Garfinkel, 2013). The behavioral measurement, however, can also be biased by autonomic evaluation and appraisal (R. Smith & Lane, 2015). In accordance with this view, a previous study found that the perceived unpleasantness of bitter taste and pain threshold/tolerance were related to somatosensory amplification, the tendency to experience the bodily sensations as intense, noxious and disturbing; while heartbeat tracking and balancing ability, and the intensity of bitter taste were not (Ferentzi et al., 2017). This result indicates that the evaluation of the interoceptive signals that have a threatening quality and can be regarded as 'homeostatic emotions' (Craig, 2003a), might be more likely to evoke responses, than the evaluation of the information belonging to other sensory channels. In other words, ascending sensory information is subject to low-level evaluation. As 'discrete body features' are integrated at the level of the mid and anterior insula to the ‘whole-body pattern’ (R. Smith & Lane, 2015), a behavioral or verbal report of these sensations is necessarily preceded by low level evaluative processes. Due to these early automatic processes, the objective comparison of different introceptive channels is problematic.

Thus, the functions of the interoceptive channels and their relation to other psychological factors have a crucial role in the interpretation of our results. The three channels that loaded consistently on different factors (pain, bitterness, and gastric perception) in our findings represent three distinct subjective sensations. Even if we (based on intuition) presume the existence of a general interoceptive sensitivity level, it might be the case that these modalities have different significance and function than the general interoceptive level. The information provided by these channels is important for the organism in its own right. Therefore, they do not seem to contribute to the ‘common sensation’, but have their distinct and clearly recognizable representations. This is in line with the presumption that different interoceptive channels are not equally relevant from the viewpoint of survival (Ferentzi et al., 2017).

Single and multichannel approaches

In some specific cases, a single interoceptive modality is significant on its own. Thus, the investigation of this modality might be warranted. For example, increased heart rate, an indicator of higher arousal, is a frequently described characteristic of anxiety disorders. Therefore, heartbeat perception tasks might be a relevant tool to assess this specific interoceptive sensitivity (Domschke et al., 2010; Van der Does et al., 2000). Similarly, some variations of the water load test might be a helpful paradigm to explore the background of gastric disorders, e.g. functional dyspepsia (Boeckxstaens et al., 2001; K. L. Koch, Hong, & Xu, 2000; Mimidis, 2007).

There are cases, on the other hand, where the investigation of a single channel does not appear an appropriate practice. For example, although meditation is assumed to improve the sensation of bodily signals, several studies using heartbeat perception task did not show differences between meditators and non- meditators (Khalsa et al., 2008; Melloni et al., 2013; Nielsen & Kaszniak, 2006; Otten et al., 2015), while one study using respiratory task led to mixed results (Daubenmier et al., 2013).

There are multichannel paradigms of interoception that represent a different approach. A study investigated the ability of healthy young adults to adjust their cardiovascular parameters during bicycle ergometer exercise to a previously experienced level (Kollenbaum, Dahme, & Kirchner, 1996). Out of the measured variables (heart rate and blood pressure) only heart rate was reproduced with high consistency by participants, which supports the idea that interoceptive accuracy cannot be generalized across channels.

Physiological or neurological dysfunctions and the chronic mal-functionality of an interoceptive channel might represent a good opportunity to understand the interoceptive system better. A study introducing a patient with external cardiac assist supports the existence of different neural pathways of heartbeat perception (Couto et al., 2014). Another study investigated two patients with focal brain lesions, using heartbeat perception task, and taste, smell and thermal pain stimulation, and argued for distinct neurological background of the different interoceptive channels (Couto et al., 2015). Connections between channels are also described. For example, higher olfactory thresholds predicted higher interoceptive accuracy scores, however the duration of the disease of people with olfactory dysfunction indicated reduced heartbeat tracking abilities (Krajnik, Kollndorfer, Notter, Mueller, & Schöpf, 2015). Because of the close link between heartbeat perception accuracy and affect (Pollatos, Herbert, et al., 2007; Wiens et al., 2000), one has to be careful with the interpretation of findings on the connection between interoceptive accuracy and chronic mal-functioning. The existence of a third underlying variable might represent the best explanation for the seemingly direct connection. Although functional motor disorder is associated with lower heartbeat perception scores, reduced interoceptive accuracy also predicted depressive symptoms and self-objectification (Ricciardi et al., 2016).

Limitations and future research

The present study is not without limitations. First, conceptually distinct approaches were used in the measurements. One type of the assessments applied external stimuli (i.e. pain, bitter liquid, water) to induce subjective ratings, while the perception of the more or less natural operation of the given sensory channel was measured by the assessment of heartbeat tracking and balance. Accordingly, the rating of the sensory channels was also different: in the case of pain, bitter liquid and water, the tasks measured the sensitivity to a standardized stimulation; while in the case of heartbeat tracking and balance, the tasks required internal focus without an additional stimulus. The proprioceptive task represents another approach that involves detection and active reproduction. Moreover, as automatic evaluation takes place at lower levels of central processing on ascending information, it is not easy to draw a line between the measures of interoceptive accuracy, subjective sensation and its subjective evaluation, especially as the later might be easily related to emotional states (R. Smith & Lane, 2015). From a theoretical point of view, these conceptual differences in the assessment of interoceptive accuracy make the direct comparison of different channels difficult, which might result in a decrease in the estimated strengths of associations. Concerning the statistical analysis, missing values were handled with pair-wise exclusion that might have impacted the results.

Other methodological issues might have also influenced the results. For example, heartbeat perception accuracy values obtained by different paradigms often show no or weak association only (Ring et al., 2015; Schulz et al., 2013). Similarly, the measurement of proprioception has several different paradigms (Han et al., 2016), and other proprioceptive tasks might relate to the other interoceptive channels differently. For example, the perception of the joints of the legs might be more connected with balance ability. The measurement of the gastric sensitivity also has different approaches, with the different types of water load or drinking tests (Mimidis, 2007) representing only a specific subtype. These conceptual and methodological differences should be taken into consideration in future multimodal interoception studies.

Conclusion

Interoceptive sensitivity assessed by using one sensory modality only cannot be generalized to other modalities. Interoceptive channels carrying crucial information for survival (e.g. pain, bitterness, and gastric perception) are not integrated with the other investigated channels.

5. Do body related sensations make feel us better? Subjective well-being is associated only with the subjective aspect of interoception

(STUDY 4)[6]

5.1. Introduction

The term interoceptor originally referred to receptors receiving and transmitting signals from the visceral organs, and was distinguished from proprioceptors (i.e. receptors collecting information from the muscles and joints) and exteroceptors (i.e. receptors of the external senses) (Sherrington, 1906). Recently, the concept of interoception has became more inclusive. In the broadest sense, it encompasses proprioceptive, tactile and thermal information, pain, and also the phenomenological experience of body state (Ceunen et al., 2016; Craig, 2015; Khalsa et al., 2018; Mehling et al., 2009; Manos Tsakiris & Critchley, 2016; Wiens, 2005). Interoception is a multidimensional construct, consisting of at least two independent dimensions: the subjective-phenomenological aspect (interoceptive sensibility, as assessed by questionnaires), and the ability to detect internal sensory events (interoceptive accuracy, measured using behavioral tasks) (Garfinkel, Seth, et al., 2015). In the literature, a variety of names are applied to both constructs (Ceunen et al., 2013; N. A. S. Farb et al., 2015; Garfinkel & Critchley, 2013; Yoris et al., 2015). To avoid confusion, we follow the terminology of Garfinkel et al. (2015) throughout this paper, i.e. the self-report aspect is called interoceptive sensibility (IS), and the aspect measured with behavioral tasks is referred to as interoceptive accuracy (IAc).

The exact operationalization and measurement of both constructs are problematic. Concerning IS, the phenomenological aspect of interoception, there are slight differences among authors regarding the exact definition. Garfinkel et al. (2015), for example, consider the Body Perception Questionnaire of Porges (1993) a tool to assess interoceptive sensibility, whereas Mehling et al. (2009) mention the same

6 The present chapter is the exact copy of the following paper: Ferentzi, E., Horváth, Á., & Köteles, F. (2019). Do body-related sensations make feel us better? Subjective well-being is associated only with the subjective aspect of interoception. *Psychophysiology*, *56*(4), e13319. https://doi.org/10.1111/psyp.13319

measure among the appropriate questionnaires assessing body awareness, along with the Body Awareness Questionnaire (Shields et al., 1989). The clear distinction between the two concepts is not always clear or justified by ecological validity (Craig, 2002; Mehling et al., 2012). The concept of body awareness was developed before the modern definition of interoceptive sensitivity (Garfinkel, Seth, et al., 2015), and defined as the beliefs about one's sensitivity to normal (i.e. non-emotional and non-pathological) body processes and changes (Shields et al., 1989). In our previous study, body awareness was described as a concept that incorporates information originating not only from the integration of sensory channels, but also from exteroceptive modalities (Ferentzi, Drew, et al., 2018). These exteroceptive cues, however, are not the classical exteroceptive senses in this context; but the sensation of the environmental cues in the relation of the interoceptive reactions (e.g. "I notice difference in the way my body reacts to various foods." Shields et al., 1989, p.66). In our view, the subjective aspect of interoception relies on such everyday experiences. Regarding the more objective aspect of interoception assessed by perceptual/detection tasks, it seemed to be modality-specific, i.e. IAc cannot be generalized across interoceptive modalities or channels (Ferentzi, Bogdány, et al., 2018; Ferentzi et al., 2017).

Although the importance of interoception is often emphasized by theoretical accounts (Damasio, 1999; R. Smith & Lane, 2015; Strigo & Craig, 2016), its actual impact on subjective well-being is an open question. Subjective well-being can be grasped with various constructs, like life satisfaction or affective experience, i.e. happiness (Krueger & Schkade, 2008). The most relevant aspect of well-being from the viewpoint of the current research is self-reported mental health (Bech, Gudex, & Johansen, 1996; Topp, Østergaard, Søndergaard, & Bech, 2015) as empirical findings suggest the relevance of interoception in mental well-being. Interestingly, the exact nature of the connection is not clear.

In the following, we are going to introduce briefly the two main approaches: one (the maladaptivity view) assumes that the perception of internal cues is potentially harmful, whereas the other (the adaptivity view) argues that a more accurate perception is the prerequisite of healthy psychological functioning. Concerning the first approach, attention focused on internal states (including perceived body states) was linked to the generation of negative emotions by a number of authors (Aronson, Barrett, & Quigley, 2006; Barsky, 1979; Duval & Wicklund, 1972; Watson & Clark, 1984). Similarly, body focused attention was considered maladaptive in the medical tradition, as it can amplify body sensations, turn normal sensations to symptoms, and might lead to health anxiety and hypochondriasis (Abramowitz, Olatunji, & Deacon, 2007; Barsky et al., 1988; Barsky & Klerman, 1983; Olatunji, Deacon, Abramowitz, & Valentiner, 2007). According to the adaptivity view, however, awareness of body cues can be helpful to the prevention and management of various chronic diseases (Bakal, 1999; Bakal et al., 2008; Mehling et al., 2009), theoretically might contribute to self-identity (Damasio, 1999; Daubenmier, 2005; Rogers, 1959), and enhance mind-body integration (N. A. Farb et al., 2015; Mehling et al., 2012, 2011).

The use of questionnaires to measure well-being and IS might provide a more direct answer to the question of adaptivity. Cross-sectional empirical studies consistently revealed weak to moderate ($r = 0.09 – 0.42$, $p < 0.05$) positive association between IS (as assessed by the Body Awareness Questionnaire, the Multidimensional Assessment of Interoceptive Awareness scale and the Somatic Absorption Scale) and various indicators of psychological and subjective well-being (as assessed by the Satisfaction with Life Scale, the Scales of Psychological Well-Being and the short Well-Being Index of WHO) (Brani, Hefferon, Lomas, Ivtzan, & Painter, 2014; Hanley, Mehling, & Garland, 2017; Köteles et al., 2012; Sági, Szekeres, & Köteles, 2012; Tihanyi, Böőr, Emanuelsen, & Köteles, 2016). For example, well-being as assessed by the Scales of Psychological Well-Being (Ryff, 1989) showed weak to medium associations with 7 of the 8 sub-scales of the Multidimensional Assessment of Interoceptive Awareness scale (Hanley et al., 2017). Similarly, Body Awareness Questionnaire scores (Shields et al., 1989) showed moderate associations with the level of self-reported well-being as assessed by the 5-items long Well-Being Index of WHO (Tihanyi, Böőr, et al., 2016). These findings are in accordance with the adaptivity approach, although the question of causality is yet to be answered.

Concerning the association between IAc and well-being, empirical evidence is mixed. For example enhanced cardiac perception is associated with anxiety disorders (Domschke et al., 2010; Ehlers, 1995; Ehlers & Breuer, 1992). In a similar vein, higher sensitivity to gastric fullness, as assessed by impaired drinking capacity, was related to functional dyspepsia (Boeckxstaens et al., 2001; M. P. Jones et al., 2003; Van Den

Elzen, Bennink, Holman, Tytgat, & Boeckxstaens, 2007). However, intuitive eating, often described as a characteristic related to well-being, is also associated with higher heartbeat perception scores (Herbert, Blechert, Hautzinger, Matthias, & Herbert, 2013). Similarly, IAc had a down-regulating effect on affect-related arousal when the emotion regulation strategy of reappraisal was used (Füstös, Gramann, Herbert, & Pollatos, 2013), and associated with both cognitive and affective empathy (Grynberg & Pollatos, 2015). To our knowledge, however, no empirical study has investigated the direct connection between interoceptive accuracy and subjective well-being in healthy individuals to date.

The theoretical approach to proprioceptive information is rather different for several reasons. First, the status of joints and muscles can be made conscious by attention to a great extent (Cameron, 2002). Second, it represents an important source of self-schema, i.e., the procedural representation of the body (Frederique de Vignemont, 2010; Gallagher, 2005), and the feeling of body ownership (Gallagher, 1998; Manos Tsakiris, 2010). These theoretical considerations suggest a positive association between proprioceptive accuracy and healthy functioning. Empirical studies with findings that support this relationship investigated patient groups, for example a negative association has been found between schizophrenia and somatosensory task performance (i.e., a proprioceptive deficit) (Chang & Lenzenweger, 2005; Ritzler & Rosenbaum, 1974; Rosenbaum, Flenning, & Rosen, 1965), although null findings are also known (Leventhal, Schuck, Clemons, & Cox, 1982). A study investigating fibromyalgia reported no difference between patients and healthy controls in the proprioceptive accuracy of the knee (Ulus, Akyol, Tander, Bilgici, & Kuru, 2013); while other findings indicate that people with fibromyalgia rely more on visual feedback in the proprioceptive task of the upper arm (Bardal, Roeleveld, Ihlen, & Mork, 2016). A narrative review on knee osteoarthritis indicated impaired proprioceptive accuracy of the knee of the patients (Knoop et al., 2011). Similarly, a systematic review and meta-analysis on chronic, idiopathic neck pain found impaired proprioception among patients while performing the head-to-neutral reposition test (Stanton, Leake, Chalmers, & Moseley, 2016). Somatoform patients, however, showed higher proprioceptive accuracy than healthy controls (Scholz, Ott, & Sarnoch, 2001). The interpretation of these results is problematic, as impairment might have several reasons, and to unfold causality experimental investigation is needed (Sharma & Pai, 1997). As physical competence relies partly on the processing of proprioceptive information (Han, Anson, Waddington, & Adams, 2014), the direct positive association between proprioception and healthy psychological functioning appears logical.

Although interoceptive sensibility and interoceptive accuracy are more or less independent dimensions, their interaction cannot be excluded. Visceroceptive information can reach consciousness in individuals with high interoceptive accuracy, and positively impact interoceptive sensibility which could result in improved well-being. Similarly, a high level of proprioceptive accuracy accompanied by high level of interoceptive sensibility might disproportionately increase well-being.

In the present study, it was assumed that interoceptive sensibility and interoceptive (visceroceptive and proprioceptive) accuracy are positively associated with subjective well-being in healthy individuals. More precisely, we expected that (1) interoceptive sensibility and measures of interoceptive accuracy, i.e. (2.a) heartbeat perception score, (2.b) gastric sensitivity and (2.c) proprioceptive accuracy would be positively related to subjective well-being. Moreover, (3) a positive interaction between subjective and objective aspects of interoception (i.e. interoceptive sensibility and accuracy, respectively) was also expected.

5.2. Method

Participants

Participants were undergraduate university students (n = 142, age: 21.93±3.582 yrs, 46.5% female). The average body mass index (BMI) of the sample was 22.61 (sd = 2.825) which is within the normal range. Resting heart rate (HR) was 73.16 (sd = 13.995). Exclusion criteria were acute infections, injuries of the upper limb that might influence the performance in the proprioceptive task, and the use of alcohol in the previous 12 hours. The investigation was part of a broader study on interoception, whose results have already been published (Ferentzi, Bogdány, et al., 2018), the overlapping variables between the two investigated datasets are the three measures of interoceptive accuracy. The sample size of the individual variables might be smaller than 142 due to missing data (see Table 12). The study was allowed by the local Research Ethical Committee, all participants signed an informed consent form prior the measurements.

Procedure

Interoceptive accuracy measurements occurred in random order (see: Ferentzi, Bogdány, et al., 2018). The Hungarian version of the questionnaires were filled out on-line. All the assessments were conducted within a 5-week time period.

Questionnaires

The shortened version of the *Well-Being Index* of WHO (WHO-5) (Bech et al., 1996) measures subjective well-being (positive mood, relaxation, activity, sleep quality) on a 4-point Likert scale with 5 items of a single overall scale. It is a widely used measure of subjective mental well-being (Topp et al., 2015). Higher scores refer to higher well-being. There is validated Hungarian version of the scale with a Cronbach's alpha coefficient of 0.85 (Susánszky, Konkoly Thege, Stauder, & Kopp, 2006), while in the present study, it was 0.783.

Interoceptive sensibility is assessed with the *Body Awareness Questionnaire* (BAQ) (Shields et al., 1989), an 18-item scale that measures the attentiveness to non-pathological and non-emotive body processes on a 7-point Likert scale. Higher scores refer to higher perceived awareness of body sensations. In the Hungarian validation study the Cronbach's alpha was 0.82 (Köteles, 2014), and because the original factor structure was not replicated in the validation study, we did not calculate sub-scale scores. In our recent study, the Cronbach's alpha was 0.809.

Patient Health Questionnaire Somatic Symptom Severity Scale (PHQ-15) (Kroenke, Spitzer, & Williams, 2002) is a 15-item scale that measures the prevalence of the most common body symptoms (e.g. headache, insomnia) in the last four weeks on a 3-point Likert scale. Higher scores indicate more and more serious symptoms. The Hungarian version of the scale is widely used (Salavecz, Neculai, Rózsa, & Kopp, 2006; Stauder & Konkoly Thege, 2006; Szemerszky, Köteles, & Bárdos, 2009). In the present study, the Cronbach's alpha of the scale was 0.754.

Measures of interoceptive accuracy

Heartbeat perception was assessed by a slightly modified version of the mental tracking task (Schandry, 1981). Participants counted their perceived heartbeats silently in a seated position during three different time periods presented in random order (30 sec, 45 sec and 100 sec; after a 15 sec long practice). Participants were asked to breath regularly while focusing on their heartbeats. They were encouraged to count slight and ambiguous heartbeat related sensations, but asked not to count anything if they did not feel anything. Taking the pulse or modification of the breathing were not allowed. Heartbeats were assessed using the Polar Fitness Test of RS-400 Polar watch and the matching chest strap and transmitter (POLAR WearLink; Polar Electro, Kempele, Finland) (Ferentzi, Drew, et al., 2018). For each trial, the following formula has been calculated: 1−|(recorded heartbeats−counted heartbeats)/recorded heartbeats|. The average provided the score of heartbeat perception accuracy from 0 to 1; higher values indicate higher levels of accuracy. The Cronbach's alpha coefficient of the Schandry-task was 0.904.

Gastric sensitivity was measured with a modified version of the water load task (Boeckxstaens et al., 2001). Participants were asked to drink five times the same amount of water (1 ml for each cm of their body height, e.g. 175 ml for a person with a height of 1.75m) during a fixed time period (in 60 sec). To make participants unable to estimate the amount of water, it was provided in non-transparent bottles, and they were allowed to lift them or change their position; there was only a little hole on their top, with a thick straw for drinking. The change in the subjective fullness was rated on visual analogue scale after each drinking sessions. Gastric sensitivity was calculated by subtracting the rated fullness value of the first drinking session from that of the fifth session; higher values indicate higher levels of sensitivity.

Proprioceptive accuracy of the elbow joint has been investigated with a device developed upon the basis of the one used by Goble (Goble, 2010), assessing proprioceptive position matching ability. Participants seated with their arms at shoulder heights, both forearms laying on a horizontally rotatable wooden board. The axis of the elbow joint was positioned above the rotating axis of the board. In this setting, the participant was able to rotate the board by changing angle of the elbow joint. The task of the participants was to replicate the position of the forearm (i.e. the actual angle of the elbow joint, randomly selected between 150 and 30 degrees) with the other forearm with closed eyes. Before each trial, both hands were fully stretched. There were five trials per hand, the starting hand was randomly selected. Proprioceptive error was calculated as the absolute value of the difference between the degree of the two positions (i.e. the one to reproduce and the reproduced); finally, values were averaged. Higher values of proprioceptive error indicate lower levels of proprioceptive accuracy.

Statistical analysis

Statistical analysis was carried out using the SPSS v21 software. As Shapiro-Wilk test indicated significant deviations from normality, correlation analysis was conducted using Spearman correlation. To estimate variables' independent contributions to subjective well-being, three multiple linear regression analyses were carried out with WHO-5 score as criterion variable. In these analyses, the natural logarithm of PHQ-15 score was used to better fit the criterion of normality. Similarly, heartbeat tracking scores were transformed to achieve a normal distribution (the demeaned data was divided by a zero centered Gauss function and the original mean was added to this resulted data series). For each analysis, variables were entered in three steps using the ENTER method: (Step 1) control variables (gender: male: 0, female: 1; PHQ-15 score to control for unpleasant body sensations), (Step 2): BAQ score and an indicator of interoceptive accuracy (heartbeat tracking ability, gastric sensitivity, or proprioceptive error), and (Step 3) an interaction term for BAQ score and the respective accuracy indicator. The interaction terms were calculated as the product of the BAQ score and the respective interoceptive accuracy score (scores were centered before multiplication, i.e. the respective mean was subtracted from the individual scores for all cases). As additional control variables, BMI and resting HR, were entered in Step 1 of the analysis that involved heartbeat tracking ability.

5.3. Results

Descriptive statistics are presented in Table 12. According to the results of the correlation analysis (Table 12), well-being showed a weak negative association with somatic symptoms and a weak positive relationship with interoceptive sensibility. Associations with indicators of interoceptive accuracy were not significant. Interoceptive sensibility was weakly positively associated with heartbeat tracking ability.

Table 12. Descriptive statistics (M±SD) and Spearman correlations with actual sample sizes (N) between the assessed variables (whole sample: N = 142)

	N	**mean±SD**	**PHQ-15 (N)**	**BAQ (N)**	**heartbeat tracking (N)**	**gastric sensitivity (N)**	**proprio-ceptive error (N)**
WHO-5	124	14.04 ±2.700	-.235** (124)	.271** (124)	.090 (105)	-.134 (84)	.099 (113)
PHQ-15	124	6.34 ±4.315		-.004 (124)	-.045 (105)	.052 (84)	-.068 (113)
BAQ	124	86.12 ±13.438			.205* (105)	-.113 (84)	-.116 (113)
heartbeat tracking	114	.54 ±.268				-.085 (81)	.062 (108)
gastric sensitivity	95	33.68 ±22.653					.002 (86)
proprio-ceptive error	128	9.40 ±3.775					

Note. Abbr.: WHO-5: WHO-Five Well-being Index; BAQ: Body Awareness Questionnaire; PHQ-15: Patient Health Questionnaire Somatic Symptom Severity Scale; *: $p < 0.05$; **: $p < 0.01$

The first regression analysis (i.e. IAc as assessed by heartbeat tracking ability) indicated a significant negative relationship between subjective well-being and somatic symptoms, and a significant positive association between well-being and interoceptive sensibility after controlling for gender, somatic symptoms, BMI, and resting HR. Interoceptive accuracy as assessed by the heartbeat tracking task and the interoceptive sensibility x interoceptive accuracy interaction term did not contribute to the WHO-5 score. The final equation explained 20.4% of the total variance of WHO-5 (p = .004) (for details, see Table 13).

Table 13. Results of multiple linear regression analysis with subjective well-being (WHO-5) as criterion variable and heartbeat tracking ability as the indicator of interoceptive accuracy

N = 97		gender	PHQ-15	BMI	Resting HR	BAQ	heartbeat tracking	body awareness x heartbeat tracking
Step 1	**B±SE**	.882±.567	-.906±.338	-.096±.095	-.031±.019			
R^2=.113;	**95.0% CIs**	-.243; 2.008	-1.577; -.235	-.285;.093	-.069;.007			
***p* = .025**	**Standar-dized β**	.173	-.284	-.106	-.165			
	p	.123	.009	.315	.108			
Step 2	**B±SE**	.785±.544	-.777±.327	-.070±.091	-.035±.018	.063±.020	-.014±.658	
ΔR^2= .091;	**95.0% CIs**	-.295; 1.865	-1.427; -.128	-.251;.112	-.072;.002	.023;.103	-1.322; 1.294	
p_{change}=.002	**Standar-dized β**	.154	-.244	-.077	-.185	.306	-.002	
	p	.152	.020	.449	.061	.002	.983	
Step 3	**B±SE**	.792±.550	-.777±.329	-.070±.092	-.035±.019	.063±.020	-.028±.670	.007±.053
ΔR^2= .000; p_{change}=.897	**95.0% CIs**	-.300; 1.884	-1.430; -.123	-.252;.113	-.072;.002	.023;.103	-1.358; 1.303	-.099;.113
	Standar-dized β	.155	-.244	-.077	-.184	.306	-.004	.013
	p	.153	.020	.452	.063	.002	.967	.897

Note. Abbr.: WHO-5: WHO-Five Well-being Index; BAQ: Body Awareness Questionnaire; PHQ-15: Patient Health Questionnaire Somatic Symptom Severity Scale; BMI: Body Mass Index; HR: Heart rate

Similar to the first regression analysis, the second analysis (i.e. IAc as assessed by gastric sensitivity) indicated a significant negative relationship between subjective well-being and somatic symptoms, and a significant positive association between well-being and interoceptive sensibility even after partialling out gender and somatic symptoms. Interoceptive accuracy as assessed by the gastric perception task did not contribute significantly to the WHO-5 score. However, the interaction term was significant, indicating a negative relationship, i.e. the association between well-being and gastric perception accuracy is positive only for below average levels of interoceptive sensibility, while the relationship is negative when interoceptive sensibility is average and above average (Figure 2). The final equation explained 19.1% of the total variance of WHO-5 (p = .005) (for details, see Table 14).

Figure 2. Gastric sensitivity mediates the association between interoceptive sensibility and well-being. Abbr.: BAQ: Body Awareness Questionnaire; WHO-5: WHO-Five Well-being Index

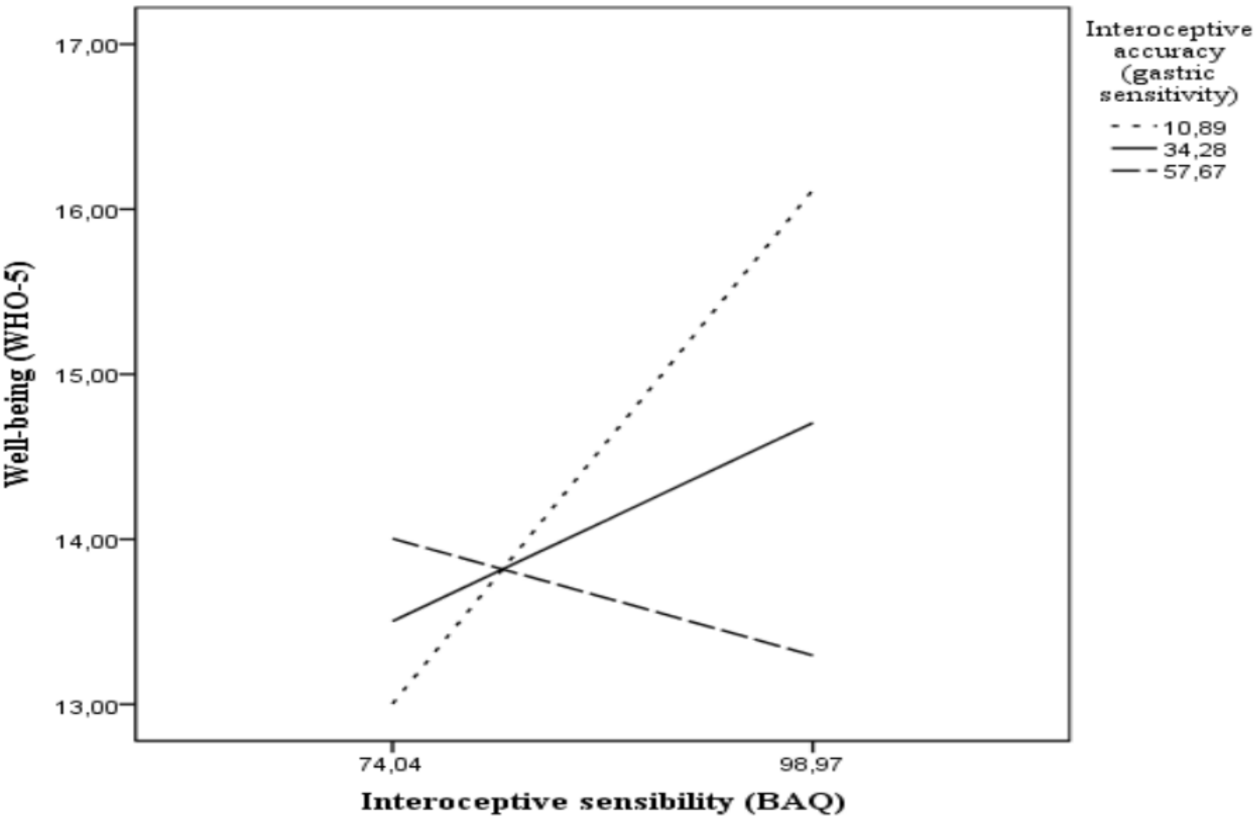


Table 14. Results of multiple linear regression analysis with subjective well-being (WHO-5) as criterion variable and gastric sensitivity as the indicator of interoceptive accuracy

N = 83		**gender**	**PHQ-15**	**BAQ**	**gastric sensitivity**	**body awareness x gastric sensitivity**
Step 1	**B±SE**	.902 ±.577	-.735±.370			
R^2 = .058; *p* = .090	**95.0% CIs**	-.245; 2.050	-1.471;.001			
	Standardized β	.178	-.227			
	p	.122	.050			
Step 2	**B±SE**	.956 ±.564	-.779±.362	.048±.022	-.011 ±.012	
ΔR^2=.067; p_{change} = .055	**95.0% CIs**	-.166; 2.078	-1.499;-.059	.005;.091	-.034;.012	
	Standardized β	.189	-.240	.234	-.101	
	p	.094	.034	.030	.347	
Step 3	**B±SE**	.834 ±.548	-.688±.352	.049±.021	-.020 ±.012	-.003 ±.001
ΔR^2=.065; p_{change} = .015	**95.0% CIs**	-.257; 1.926	-1.390;.013	.007;.091	-.044;.003	-.005; -.001
	Standardized β	.165	-.212	.241	-.186	-.271
	p	.132	.054	.021	.090	.015

Note. Abbr.: WHO-5: WHO-Five Well-being Index; BAQ: Body Awareness Questionnaire; PHQ-15: Patient Health Questionnaire Somatic Symptom Severity Scale

Finally, the third regression analysis (i.e. IAc as assessed by proprioceptive error) indicated a significant negative relationship between subjective well-being and somatic symptoms, and a significant positive association between well-being and interoceptive sensibility. Intecoceptive accuracy as assessed by the proprioceptive accuracy task and the body awareness x proprioceptive error interaction term did not contribute to the WHO-5 score. The final equation explained 16.0% of the total variance of WHO-5 (*p* = .002) (for details, see Table 15).

Table 15. Results of multiple linear regression analysis with subjective well-being (WHO-5) as criterion variable and proprioceptive error as the indicator of interoceptive accuracy

N = 113		**gender**	**PHQ-15**	**BAQ**	**proprio-ceptive error**	**body awareness x proprio-ceptive error**
Step 1	**B±SE**	.194±.523	-.944±.333			
R^2 = .071;	**95.0% CIs**	-.843; 1.231	-1.604; -.284			
***p* = .018**	**Standar-dized β**	.036	-.275			
	p	.712	.005			
Step 2	**B±SE**	.424±.510	-.891±.320	.062±.019	.123±.105	
ΔR^2 = .089;	**95.0% CIs**	-.587; 1.436	-1.526; -.257	.025;.099	-.085;.331	
p_{change} = .004	**Standar-dized β**	.079	-.260	.304	.107	
	p	.408	.006	.001	.242	
Step 3	**B±SE**	.407±.517	-.890±.322	.062±.019	.120±.106	-.002±.008
ΔR^2 = .001;	**95.0% CIs**	-.617; 1.431	-1.527; -.252	.024;.099	-.091;.330	-.018;.013
p_{change} = .793	**Standar-dized β**	.076	-.259	.301	.104	-.024
	p	.433	.007	.001	.261	.793

Note. Abbr.: WHO-5: WHO-Five Well-being Index; BAQ: Body Awareness Questionnaire; PHQ-15: Patient Health Questionnaire Somatic Symptom Severity Scale

5.4. Discussion

In a cross-sectional study with the participation of young healthy adults, subjective well-being showed weak to medium level associations with interoceptive sensibility even after controlling for gender and negative body related sensations (i.e. perceived symptoms). However, no associations with interoceptive accuracy (as assessed by heartbeat tracking ability, gastric sensitivity, and the proprioceptive error with respect to the elbow joint) were found. Moreover, an interaction between interoceptive sensibility and gastric sensitivity was revealed.

The positive association between subjective well-being and interoceptive sensibility (i.e. the subjective or perceived aspect of interoception) replicates the findings of previous studies (Hanley et al., 2017; Tihanyi, Böőr, et al., 2016; Tihanyi, Sági, et al., 2016). One explanation is that better psychological functioning and lower levels of perceived stress enable healthy individuals to allocate more attentional resources to various stimuli, including information originating in the body (Köteles et al., 2013). The finding that body-mind interventions have a positive impact on interoceptive sensibility (Bornemann et al., 2015; Fissler et al., 2016; Mehling et al., 2013; Rani & Rao, 1994) also supports this idea. It is also possible, however, that a more positive cognitive-emotional condition simply biases self-reports in a positive direction (Ferentzi, Drew, et al., 2018). Finally, in accordance with the tenets of body-mind theorists, paying more attention to the body (i.e. gut feelings, emotions) may also lead to better functioning and improved well-being (Bakal, 1999; Daubenmier, 2005; N. A. Farb et al., 2015; Mehling et al., 2009, 2011). This association might be behaviorally mediated, e.g., more focus on body sensations might enable the individual to recognize symptoms of diseases and seek medical help earlier or change potentially risky behaviors in their early phase (Bakal, 1999; Fogel, 2013). However, interoception is a special perceptual process where raw sensory input plays a less salient role in shaping the conscious content than in the case of exteroception (Ádám, 1998). In other words, non-pathological interoceptive sensory information is usually ambiguous thus its perception of heavily influenced by top-down factors such as expectations, previous experiences, environmental cues (Brown, 2004; Friston, 2005; Friston et al., 2006; Pennebaker, 1982). In conclusion, the aforementioned top-down factors will play a substantial role in the behaviors improving mental and physical health. The strength of the association (interoceptive sensibility explained approximately only 6-8 % of the variance of well-being) appears realistic; as both constructs are influenced by a number of various factors, a substantially stronger association would be spurious.

Body focused attention does not necessarily improve the accuracy of detection of body signals (Ceunen et al., 2013; Silvia & Gendolla, 2001); in other words, there is a considerable dissociation between perceived and actual body related events (Ainley & Tsakiris, 2013; Ferentzi et al., 2017; Pennebaker, 1982). For example, subjective somatic symptoms were not related to either indicator of IAc in the current study, which basically reflects the often reported independence of symptom reports and body events (van den Bergh, Witthöft, et al., 2017). Similarly, power posing (i.e. voluntarily adopting powerful postures to improve performance) evoked self-reported changes in mood but did not influence hormone levels and behavior in risky situations (Ranehill et al., 2015). Although interoceptive sensibility was weakly associated with the cardiac indicators of IAc in our study, IAc did not contribute to subjective well-being after controlling for gender, BMI, and resting HR in the regression analysis, and no interaction between interoceptive sensibility and cardioception was revealed. Taken into consideration that the regression analyses were also controlled for somatic symptoms (i.e. sensations from the body that are negative by definition), it can be concluded that the accuracy of detection of interoceptive changes do not have a direct positive or negative impact on well-being.

The only interaction we found (i.e. gastric sensitivity moderates the association between interoceptive sensibility and well-being) only partially supports the adaptivity hypothesis, as the contribution of interoceptive sensibility to well-being is positive only for low and medium levels of gastric sensitivity. According to our result, the interaction between gastric sensitivity and interoceptive sensibility contributes to higher level of well-being in the two following cases: firstly, if low to medium gastric sensitivity is accompanied by high interoceptive sensibility; and secondly, if high gastric sensitivity is accompanied by low interoceptive sensibility. We can only speculate about the interpretation of this result, as well as why it was found for gastric sensitivity only. First of all, gastric fullness above a certain level is an unpleasant feeling, which leads to terminating the ongoing food and drink intake. This feeling occurs on a regular basis for everyone, whereas heart related and conscious proprioceptive experiences are less frequent under everyday circumstances. Concerning the interpretation of the interaction, high gastric sensitivity can turn the positive association between well-being and interoceptive sensibility into negative because increased body focus might amplify the unpleasantness of the feeling of distension. This is in accordance with the view, that bottom-up and top-down processes occur and interact with each other at almost every level of the interoceptive sensory system (R. Smith & Lane, 2015). Thus, making bodily sensations more conscious might not be beneficial in all cases; it is also an open question, however, whether our finding represents clinical relevance. We also would like to emphasize, that this interpretation is speculation only, and the result needs to be confirmed by the replication of the study.

One of the limitations of the current study are, that its conclusions are valid for healthy individuals only; atypical interoception may lead to issues in psychological development and represent a general susceptibility to psychopathology (Murphy et al., 2017). Extremely low and high levels of interoceptive accuracy with respect to one single modality might also have modality specific pathological consequences. However, interoceptive accuracy is not a unitary construct, i.e., various interoceptive modalities are independent of each other with respect to IAc (Ferentzi, Bogdány, et al., 2018). This also implicates that differences in the accuracy of detection of various bodily cues and modalities within the normal domain can even competing with each other, providing a complex body sensation (R. Smith & Lane, 2015). Thus, sensitivity with respect to a single channel does not necessarily influence everyday psychological functioning. Interoceptive sensibility, on the other hand, represents a more unitary (i.e. integrated) construct, therefore it may impact self-reported characteristics such as well-being.

Issues related to the sensory measurements of interoception have to be mentioned among the limitations of the current study. As IAc is not generalizable across modalities, the current study assessed three interoceptive channels. However, other modalities might be more relevant concerning subjective mental well-being, such as breathing, the change of heart rate (rather than its actual state), sweating, or the sensation of body temperature change. The context and the interpretation of the bodily cues were also not investigated here, although both might influence self-rated well-being. Moreover, the Schandry task has received several criticisms recently, and is not considered a reliable indicator of cardioceptive accuracy by some authors (Brener & Ring, 2016; Ring & Brener, 2018). Finally, participants were not screened for mental disorders and chronic conditions that might impact their performance. These issues, and the characteristics of the sample (young adult, with a relatively high subjective well-being score) limit the external validity of the findings.

In summary, subjective well-being of healthy young adults is associated with the subjective (perceived) aspect of interoception, but not related to interoceptive accuracy. Thus, the level of well-being depends more on our subjective bodily report than on the actual accuracy of our bodily sensations.

6. General discussion of the findings[7]

This publication based doctoral dissertation presents the findings of four studies. In this studies, I investigated the test-retest reliability of and the association between the two major dimensions of interception (i.e. interoceptive sensibility, as assessed with self-reported questionnaires, and interoceptive accuracy, as assessed with sensory tasks), see Study 1, Ch.2. Furthermore, it also examined the associations between various channels of interoceptive accuracy, i.e. heartbeat perception, pain perception, sensitivity to the bitter taste, and balancing ability (Study 2, Ch,3); and additionally, gastric sensitivity, and proprioceptive accuracy with respect to the elbow joint (Study 3, Ch.4). Finally, Study 4 (Ch.5) investigated the associations between the measures of interoceptive accuracy (i.e. heartbeat perception, gastric sensitivity, and proprioceptive sensitivity), interoceptive sensibility, and subjective well-being. Further self-reported variables were also included, such as the Big Five personality factors and somatosensory amplification (Study 2, Ch.3).

6.1. Brief summary of the findings

According to the results, both interoceptive accuracy (as assessed with the Schandry-task, Schandry, 1981) and interoceptive sensibility (as assessed with Body Awareness Questionnaire, BAQ, Shields et al., 1989) showed good test-retest reliability (temporal stability) over an 8-week period. They were not associated at baseline with each other, and also did not predict each other over an eight weeks time period (Study 1, Ch.2). Another study showed a weak association between the variables (Study 4, Ch.5).

7 The Discussion contains translated and edited parts of the following papers:
Ferentzi, E., Tihanyi, B. T., Szemerszky, R., Dömötör, Z., György, B., & Ferenc, K. (2018). Interocepció. Narratív összefoglaló [Interoception. Narrative review]. *Mentálhigiéné És Pszichoszomatika*, *19*(4), 297–334. https://doi.org/10.1556/0406.19.2018.014;
Pollatos, O., & Ferentzi, E. (2018). Embodiment of Emotion Regulation. In G. Hauke & A. Kritikos (Eds.), *Embodiment in Psychotherapy: A Practitioner's Guide* (pp. 43–55). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-92889-0_4

The assessed modalities of interoceptive accuracy (i.e. heartbeat perception, pain perception, sensitivity to the bitter taste, and balancing ability) were not associated with each other (Study 2, Ch.3). A further investigations, involving two more sensory channels (i.e. gastric sensitivity and the proprioceptive accuracy of the elbow joint) showed significant correlation only between modalities belonging to the same sensory channel (i.e. level of pain threshold and tolerance, bitter intensity and unpleasantness, gastric fullness and unpleasantness). Similarly, the three factors revealed by factor analyses represented the three aforementioned channels. In summary, no associations among sensory channels or modalities were revealed in two independent studies, and the conclusion was drawn that interoceptive accuracy is not a unitary construct.

Concerning the variables measured with questionnaires, somatosensory amplification was weakly related to introversion and emotional lability factors of the Big Five. Additionally, it showed weak to medium level associations with the perception of pain, unpleasantness of bitter taste, and body awareness. Interoceptive sensibility was weakly associated with openness and conscientiousness, but was not related to any of the sensory channels of interoceptive accuracy (Study 2, Ch.3).

Subjective well-being was related only to self-reported aspect of interoception (i.e. interoceptive sensibility) after controlling for gender and perceived symptoms. It was not associated with interoceptive accuracy, as assessed by heartbeat tracking, gastric sensitivity, and proprioceptive tasks (Study 4, Ch.5). Additionally, an interaction between interoceptive sensibility and gastric sensitivity was found.

6.2. About the independence of the major dimensions of interoception

The finding of Study 1, that the two main dimensions (i.e. interoceptive accuracy and sensibility) are independent from each other is in accordance with the majority of findings reported in the literature (Ainley & Tsakiris, 2013; Emanuelsen et al., 2015; Garfinkel, Seth, et al., 2015; Khalsa et al., 2008; Yoris et al., 2015). The seemingly conflicting result of Study 4 is not totally contradictory, if we consider the fact that only a weak association was revealed, which seems negligible from a practical (e.g. clinical) point of view. Additionally, BAQ scores were only related to heartbeat perception scores, but to none of the other measures of interoceptive accuracy.

Very probably, there are several different factors in the background of the missing or low association. Firstly, the two dimensions represent two very different methods for the assessment of interoception. What one thinks about his or her own interoceptive sensibility is biased by several factors, such as limited memory capacity, self-serving biases, contextual effects, or the effect of past memories of various significance. Interoceptive accuracy is also not without biases, but the nature of the influencing factors are different, as we saw above (see Ch.1.2).

In the case of the sensory tasks, participants are asked about their current performance, while the questionnaires of interoceptive sensibility investigate the trait-like characteristics of interoception. Even if interoceptive accuracy seems to be a relatively stable characteristics, these two approaches (actual performance vs. general perceived ability) differ fundamentally.

Moreover, there is another aspect in which the two methods differ significantly. The sensory measures of interoceptive accuracy usually assess only one interoceptive channel. Even if multiple modalities are involved in a study, this scope is still very limited as compared to the diverse items of the questionnaires.

There are some exceptions, however, mainly among the relatively early studies. Blanchard et al., for example, selected five items from the APQ referring to heart activity only (Blanchard, Young, & McLeod, 1972); however, their study focused on the modification of the heart rate and not on its perception, which is a different task. They found that participants with low average heart function related APQ-scores successfully raised and lowered their heart rates, while people with higher self-reported awareness were not able to achieve significant changes. Other studies identified participants as cardiac aware or unaware using two simple items (i.e. “loud pounding heart” and “increased heart rate”) (Sirota, Schwartz, & Shapiro, 1974, 1976); based on their everyday life experiences, they had evaluate how much these sensations changed when they felt general fear or anxiety. Just like in the study mentioned before, the task did not target the perception of the heartbeats, but the alteration of the heart rate.

The perception or detection of the visceral (Hölzl et al., 1996), or more generally, internal bodily stimuli (R. Smith & Lane, 2015) is based on many different levels of processing. At the first sight, the information composing interoceptive sensibility is more complex and diverse than that of interoceptive accuracy. So to say, the former represents the highest perceptual level, including not only bottom up sensory information, but individual beliefs and past experiences (i.e. top-down factors). On the other hand, the sensory measures of interoceptive accuracy cannot be regarded as pure bottom-up perceptual tasks either (R. Smith & Lane, 2015). As we saw above (Ch.1.2), measures of interoceptive accuracy are also highly influenced by non-interoceptive factors such as personal belief, knowledge, cognitive capacity, or past experiences.

Modern accounts of the process of internal signals, such as the predictive coding approach (Seth et al., 2012) or the integrative neuro-cognitive model of Smith and Lane (R. Smith & Lane, 2015) identify multiple stages of information processing (both theories will be discussed below in more details). Although the stages described by these models represent different levels of consciousness, the emphasis is mainly on processes that are out of the reach of awareness. It is important to remember, that when interoceptive accuracy and sensibility are assessed, participants are operating on a conscious level (with some exception, e.g. studies investigating conditioning, De Peuterl, Van Diestl, Vansteenwegenl, Van den Berghl, & Vlaeyenl, 2011). This mean that they are fully aware of the tasks, and thinking about their responses consciously, so the two approaches (accuracy vs. sensibility) are from this point of view not completely different.

To sum up, apart from being biased by different factors, the main difference between the sensory and the questionnaire tasks in my opinion is, that while the measures of interoceptive accuracy focus on one channel only, the majority of the questionnaires cover several interoceptive channels (and, so to say, they work with an average rating of all of them). Additionally, as I have mentioned above, the sensory measures always assess state-like performance, while the questionnaires assess trait-like ability. To make the comparison of the approaches more meaningful, both methods should be state-like, and have the same focus regarding the number and type of the interoceptive sensations. Of course, the results of the two approaches might still differ, but it would reflect more clearly what is the difference between the perceived (assessed with questionnaire) and the actual (assessed with sensory measure) performance.

Last but not least, the relatively low ecological validity of the paradigms of interoceptive accuracy might be also one of the causes of the lacking association of the two approaches. I will write below about the possibility to increase ecological validity in more details (see: Ch.6.7).

6.3. About the independence of interoceptive modalities

The findings of Study 2 and 3 suggest the independence of the modalities of interoceptive accuracy. As we saw above, channels with the same function (i.e. involving negative evaluation) might be still related at certain level (Ch.2), and also, variables belonging to the same sensory modality might associate, as they represent similar information (Ch.3). Additionally, we also saw that the lack of association of the interoceptive channels does not exclude the existence of a general interoceptive ability (see Discussion of Ch.3). The question is, how this might emerge. Models describing the possible ways of processing of interoceptive information might provide an answer. Before discussing these models, I would like to address briefly a more profound, underlying topic.

In this present dissertation I chose to use the term ‘perception’, which makes sense as we talk about ‘intero-ception’. As we saw above, however, some tasks of interoceptive accuracy are called detection or discrimination tasks, as they are based on the signal detection theory. It might be the case, that the very nature of the tasks themselves (or even the sensory channels themselves) are so different, that it is quite impossible to design paradigms of meaningfully comparable measures.

First of all, some distinctions elaborated for the visual sense (i.e. detection vs. discrimination vs. identification, Sekuler & Blake, 2004), are hard to translate to the context of interoception, as the very nature of interoceptive signals is that they are often diffuse and also hard to distinguish from the integrated personal experience (Leder, 2018). Based on the work of Schmidt (Schmidt, 1986; Schmidt & Altner, 1978), Bárdos describes three stages of the interoceptive sensory processes: reception, sensation, and perception (Bárdos, 2003). During reception, a sensory receptor is activated by a stimulus. Sensation describes the primary stimulus processing, the activation of the central nervous system. Perception occurs, when the individual becomes aware of the stimulus, and the interpretation of the sensations takes place. Of course, the interoceptive stimuli do not always reach the level of consciousness.

Interoceptive information processing, however, is influenced by various factors, not only by the nature of the stimuli. In the following, I will discuss information processing in the context of interoception.

6.4. Models of information processing

In the *Introduction* of my doctoral thesis, I discussed the model of predictive coding that aimed to explain information processing (Friston, 2005; Friston et al., 2006). It was originally developed to explain how visual information is being processed, but later on it was successfully applied in the context of interoception.

The more recent model of Smith and Lane uses a different approach (R. Smith & Lane, 2015). Theoretically (besides the empirical findings of cognitive neuroscience), it is rooted very much in the theories of emotion regulation. Accordingly, the model focuses on emotion states and evaluation, and aims to integrate the two main approaches of emotions and emotion regulation (namely the cognitive theories, and the so called ‘embodied’ theories, models that emphasize the importance of the bodily signals).

The model of conscious and unconscious emotional states

The model proposed by Ryan Smith and Richard D. Lane argues that emotions are the results of multilevel appraisal mechanisms (R. Smith & Lane, 2015). Their hierarchical, neuro-cognitive framework is built on the review of the empirical evidence of neural science, and the basic notions of the embodied theories of emotions, among others on the work of Antonio Damasio and Jesse J. Prinz (Damasio, 1994, 1999; Prinz, 2004).

In their model, Smith and Lane distinguish between the so-called ‘discrete body features' and 'whole-body pattern', represented at different levels of the nervous system. Discrete body features, i.e. organ-specific activity for use in homeostatic, reflex-like regulation circles (such as the input from blood pressure-sensitive baroreceptors and their use for reflex level cardiac regulation) are represented in somatosensory cortices, posterior insula, nucleus of the solitari tract, hypothalamic nuclei and the parabrachial nucleus, while whole-body patterns are represented in the mid and anterior insula. Whole-body pattern represents the entire activity pattern of the body related to phenomenologically distinguishable bodily feelings such as being stressed or in a sad mood, corresponding to the notion that bodily feelings always refer to a whole pattern of bodily changes. Emotion concepts then occur by appraisal mechanisms involving other brain regions such as the anterior cingulate and the medial prefrontal cortices that refer to this mapping of the body-state. It is a multi-stage interoceptive/somatosensory process by which these body state patterns are detected and assigned conceptual, emotional meaning (R. Smith & Lane, 2015). These different concepts are summarized in Table 16.

Table 16: Body/Emotion perception hierarchy (based on: Smith & Lane, 2015, p. 8)

Stages	**Representation of…**	**Neural background**
1.	**discrete body features**	nucleus of the solitary tract, parabrachial nuclei, circumventricular organs, hypothalamic nuclei somatosensory cortex posterior insula
2.	**whole-body patterns**	mid- insula anterior insula
3.	**emotion concepts**	rostral anterior cingulate cortex/medial prefrontal cortex lateral anterior temporal lobe

These assumptions are in accordance with the findings of empirical studies showing that the insular cortex and the anterior cingulate cortex play crucial roles in connecting interoceptive processes and emotions (Pollatos, Gramann, & Schandry, 2007). Their activation was found to be modulated by cognitive and emotional factors in several studies. This view is also in agreement with recent findings that subjective emotional evaluation of interoceptive signals reflects processes independent from more basic perception as operationalized by interoceptive perception accuracy measures (Pollatos, Herbert, Mai, & Kammer, 2016).

The structure of the emotion regulation model (with its six neural and functional levels) has some similarities with the above introduced (Ch.1.6) predicting coding model. Here, however, the authors do not focus on information (or input) processing in general, but particularly on emotions. The regulation hierarchy is an inherent part of the framework, and cannot really be described separately, as emotion generation and regulation are not regarded as fully distinct phenomena. The six levels involve different neural systems (an aspect that will not be introduced here in detail for the sake of simplicity) that communicate with each other through efferent top-down and other regulatory signals. At each level, the information above is not available, but the higher levels can modulate the levels below (just like in case of predictive coding). Table 17 summarizes the main features of each level.

Table 17: Model of emotion regulation according to Smith and Lane (2015)

Levels	Function	Neural background
1.	**somatic/visceral reflexes**	
2.	**homeostasis**	nucleus of the solitary tract, rostral ventrolateral medulla, nucleus ambiguous, dorsal motor nucleus of the vagus
3.	**stereotypical (behavioral) activity**	hypothalamus, periaqueductal gray
4.	**fast, inflexible appraisal mechanism**	medial temporal regions
5.	**autonomic emotion regulation**	medial PFC, rostral ACC, ventromedial PFC, medial temporal lobe, dorsal ACC
6.	**voluntary emotion regulation**	dorsolateral PFC, ventrolateral PFC, dorsomedial PFC, dorsal ACC

Note: PFC = prefrontal cortex; ACC = anterior cingulate cortex

The lowest level is the level of somatic or visceral reflexes, and connected entirely to simple reflexes coordinated by peripheral nervous system and the spinal cord. The second level is the level of homeostasis, and is located in the lower brainstem. The third level involves the autonomic nervous system, and coordinates stereotypical (behavioral) activity, for example, defense reaction or thermoregulation. The activity of the fourth level is described as a fast, inflexible appraisal mechanism that is located in the medial temporal regions (e.g. amygdala). This level focuses on autonomic perceptual and cognitive mechanisms that react to simple perceptual stimuli with potential emotional significance. The fifth level is proposed to be involved with flexible autonomic emotion regulation. It is more sensitive to the context than level four, and works with a slower appraisal mechanism. The function of level six is voluntary emotion regulation that is goal directed, and involves intentions and planning. It regulates voluntary actions, such as the attempt to use suppression and reappraisal. Level six involves top-down processes that influence cognitive functions such as memory and attention, and able to change thoughts and behavior. The explicitly cognitive mechanisms such as goal directed behavior, adjustment to the norms require more time, and will take place only after the fast appraisal mechanism has activated the physiological reactions.

The framework of Smith and Lane can be regarded as a possible way to explain the disturbance of interoceptive processes involving emotions, such as depression, anxiety, and panic disorders (Domschke et al., 2010; Ehlers & Breuer, 1996; Paulus & Stein, 2010; Van der Does et al., 2000).

As we can see, the logic of the model by Smith and Lane is quite similar to the one presented by the scholars arguing for the predictive coding model. The main distinction is, as I have mentioned above, that the predictive coding model does not initially take emotions into account, while the main focus of the Smith and Lane model is emotion regulation (R. Smith & Lane, 2015).

Scholars working in the framework of the predictive coding do not necessarily involve the recent neurological findings in such a detailed way as Smith and Lane do in their model. There are attempts, however, to build out a possible neurological framework that is consistent with the predictive coding model. I will introduce one of these briefly in the following.

Embodied predictive interoception coding

The model of embodied predictive interoception coding of Barrett and Simmons has four main hypotheses regarding the neural background processes of interoception (Barrett & Simmons, 2015). According to the model, the so called agranular visceromotor regions of the cortex[8] have a significant role in the balance between the autonomic, metabolic and immunological processes of the body; including the estimation of the resources and the prediction of the requirements. Based on these estimations, the agranular visceromotor cortices send predictive information to the hypothalamus, brainstem, and spinal cord nuclei, to maintain homeostasis (Hypothesis No.1). Simultaneously, the agranular visceromotor regions also send predictive information to the primary interoceptive sensory cortex (Hypothesis No.2). Although the granular cortices[9] are architecturally capable to receive and send prediction-error signals (Hypothesis No.3), the agranular visceromotor regions are relatively insensitive to the signals of prediction-error, at least compared with the regions sending the exteroceptive predictions (Hypothesis No.4). Consequently, they are also relatively stable regarding their interoceptive predictions, and might alter their predictions slowly.

The model explains well how false interoceptive predictions might lead to chronic illnesses. The authors also provide an example, describing in details how the symptoms of depression might become chronic by time (Barrett & Simmons, 2015); an impressive train of thought supported by empirical findings that will not be introduced here in details due to its complexity. Additionally, it is presumed that as far as interoceptive predictions are also the base of any normally occurring changes in the interoceptive system (e.g. cardiac or respiratory changes), pathological mechanisms in the interoceptive system might lead to abnormal interoceptive responses to normal incoming information, such as stress cues.

The model emphasizes, that not only our previous viscerosensory experiences influence our future interpretations, but also the body recently interpreted, current state. As the authors write about this, “it is an elegantly orchestrated self-fulfilling prophecy,

8 Including the following areas: cingulate cortex (Brodmann area 24, Br 25 and Br 32), posterior ventral medial prefrontal cortex (Br 14c), posterior orbitofrontal cortex (Br 13a), and most ventral portions of the anterior insula (Barrett & Simmons, 2015).

9 Located in the primary interoceptive sensory regions of the mid- and posterior insula (Barrett & Simmons, 2015).

embodied within the architecture of the nervous system" (Barrett & Simmons, 2015, p. 9).

Summary

The above introduced models of interoceptive information processing might explain some of the difficulties of interoception research. Because interoceptive signals and sensations are very often diffuse and complex (Leder, 2018), the system is inclined to make predictions based mainly on previous and recent experiences. The nature of the prediction might be very different depending on the situation (e.g. questionnaires vs. sensory tasks) and the investigated channels (e.g. tasks or questions focusing on breathing vs. balance).

Of course, these models are frameworks only that might help to understand interoception, but might be also misleading, and, most importantly, need to be tested. Considering, however, the presumed complexity of the interoceptive information processing system, it is not very surprising that different aspects of interoception (i.e. dimensions and modalities) are not related.

6.5. Emotions and emotion regulation

Considering the significance of interoception, the scope of my doctoral thesis might be relatively narrow, as the above introduced four empirical studies do not take emotions into account; only indirectly. On the one hand, one can argue that the topic of interoceptive modalities and dimension is not connected to emotions; on the other hand, the close relation of interoception and emotions provides one of the key elements of the significance of interoception.

In the light of the findings of my thesis, it would be necessary to include more than one dimension and sensory modality of interoception if interoceptive accuracy is investigated. An exceptional case might be, if the examination of certain modalities can be supported by extra arguments, for example when a certain interoceptive modality is more informative than any other. Such case might be for example the examination of bladder sensations (Abrams et al., 2003) in the symptom syndrome of overactive bladder (Yamaguchi et al., 2007), or the investigation of respiratory resistance in asthmatic patients (Dahme, Richter, & Mass, 1996; Kifle, Seng, & Davenport, 1997).

The paradigms of heartbeat perception are widely used when the relation of emotional processes and interoception is investigated (e.g. Herbert, Pollatos, & Schandry, 2007; Pollatos, Herbert, Matthias, & Schandry, 2007; Wiens, 2005). The specificity of interoceptive modalities might be a possible argument of the usage of heartbeat perception tasks when anxiety and related disorders are examined. Heartbeat perception paradigms are, however, not restricted to this area. They are applied, as we will see in the following, in various conditions investigating multiple phenomenon related to emotions and mental health. This approach might be oversimplified and misleading (N. A. Farb & Logie, 2018), as emotion related bodily reactions (and subjective sensations) are not restricted to the changes of the heartbeat.

There are several studies showing that interoceptive accuracy is positively associated with various aspects of emotional processes. Empirical results cover different fields, such as specific emotion regulation strategies, or situations where social exclusion occurs, empathy or social fairness are required. On the one hand, these empirical results are in accordance with the above introduced model of Smith and Lane; on the other hand, these findings provide some evidence, that the ability of heartbeat perception might be indeed connected to emotion processes. In the following, I will introduce studies investigating emotion-related psychic phenomena using the mental heartbeat tracking task. Accordingly, I will name the measured interoceptive ability heartbeat perception accuracy.[10]

Heartbeat perception accuracy is a positive predictor of the success of emotion regulation, specifically the downregulation of affect-related arousal. Füstös and colleagues (Füstös et al., 2013) reported that participants with higher interoceptive accuracy were better at downregulating their negative affect evoked by unpleasant pictures. This subjective change was accompanied by reduced amplitude of the P300,an event-related brain potential measured with electroencephalography that reflects

10 I will do so because the other often used specific description (i.e. 'cardiac accuracy') might be also misleading, as various other interocptive channels can be investigated in the cardiovascular system.

arousal-related processing.

Emotion regulation in a social context is essential for mental health. A recent study investigated social exclusion with the cyberball paradigm – a computer game, where the participants' task is to toss a ball believing that they play with others (Pollatos, Matthias, & Keller, 2015). The design of the play (e.g. speed, frequency of inclusion) is controlled by the software, manipulating the level of social exclusion. Higher heartbeat perception accuracy was related to lower level of distress following social exclusion, supporting previous results (Werner, Kerschreiter, Kindermann, & Duschek, 2013).

Interoception also helps to differentiate between the emotions of others. Participants with higher heartbeat perception accuracy also display enhanced accuracy in identifying emotional facial expressions (Terasawa, Moriguchi, Tochizawa, & Umeda, 2014). Interestingly, this was especially true for expressions of sadness and happiness as opposed to disgust and anger. One possible interpretation of the results relates to the contribution of embodied simulation to the identification of different emotions. The interoceptive read-out of a physiological state evoked by an emotional cue helps to identify emotions (Singer & Lamm, 2009).

By extension, interoception is also linked to empathy: ratings of pain intensity and compassion were higher in people with enhanced heartbeat perception accuracy in response to pictures depicting painful situations, indicating that both cognitive and affective dimensions of pain draw on interoceptive processes (Grynberg & Pollatos, 2015). This finding is also consistent with the view that interoceptive accuracy enables more effective mechanisms to support the adaptive use of emotion regulation. Correspondingly, in children, better heartbeat perception accuracy is associated with higher scores of emotional intelligence and adaptability (A. Koch & Pollatos, 2014).

Deficits in the generation, representation and processing of physiological arousal have been shown to be linked to disadvantageous and riskier decision-making behavior that involves winning and losing money. Healthy individuals with heightened heartbeat perception accuracy perform better on these decision-making tasks. One frequent paradigm used is the so-called ultimatum game which is about the acceptance or rejection of proposals. There are two players, one proposer who has a certain amount of money, and one responder, who considers the offers. If the responder accepts the offer, the sum of money is split between the two players; if the offer is rejected, neither of them gets any. This paradigm is commonly used to study the tension between motives of financial self-interest and social fairness. Interoceptive accuracy has been found to moderate the extent to which autonomic changes during the game predict social behavior during the game, notably the expression of negative responses (rejection) to perceived unfairness of another person (Dunn, Evans, Makarova, White, & Clark, 2012).

A plausible interpretation of these results is that a greater accuracy in detecting bodily cues facilitates the regulation of emotional responses by enhancing the ability to discriminate between different emotional states. This might also enable to use earlier countermeasures for controlling emotional arousal. These mechanisms might be especially relevant in social situations associated with feelings of social exclusion, negative affect or empathy. This view is in accordance with empirical data showing that people with a highly differentiated emotion experience are better at regulating their emotions in everyday situations (Barrett, Gross, Christensen, & Benvenuto, 2001).

6.6. Interoception and mental health

As we discussed above, there are two major approaches to the topic of interoception and health (Ch.1.5). One argues that high level of interoception is advantageous, while according to the other, it is harmful. Additionally, many scholars investigating the topic emphasize the importance of interpretation of the bodily signals. This might be one of the explanations why self-reported well-being associated with interoceptive sensibility only (see Study 4). In the light of the above introduced theories, it is understandable how the different levels of the (interoceptive) information processing system influence each other; and consequently, how a certain level of interoception might be either beneficial or harmful for the organism, depending on further mechanisms involved, such as filtering of the incoming information, attention, expectations, and interpretation. The above introduced information processing models show how these mechanism might influence conscious perception.

In the following, I will provide some further evidence of this association. Firstly, from a theoretical point of view, namely from the field of personality psychology; and secondly, from an empirical view point, from the area of classical empirical interoception research.

Personality psychology

Some of the modern and classical theories of personality and social psychology also emphasize the importance of interoceptive (meaning here bodily) signals. These authors emphasize the benefit of interoception (in the broader sense), and argue that it is not the body focus or the perception of the bodily signals what is harmful, but the emotions and interpretation attached to these processes. These approaches emphasize the importance of life-time experience and with this, of learning.

The self-regulation-theory of Carver and Scheier (1981), for example, also emphasizes the adaptivity of self-focused attention. The perception of bodily signs plays an important role in other classical (Rogers, 1951, 1959) and more recent (Seymour Epstein, 2014) modern personality theories. A simple, early example of the organismic valuing process of Rogers when the toddler requires food based on his bodily signs. The attention turned inward, the perception and evaluation of the bodily signals play a significant role later too, as some kind of reference of the individual needs (Rogers, 1959). The dual personality theory of Epstein describes two information processing systems with complementary functions. While the rational systems is verbally coded, analytical, and involved in slow, time-consuming decisions, the other system called intuitive-experiental is quick, automatic, with emotion-driven decisions, influenced by bodily signals and sensations (Seymour Epstein, 2014). None of the two systems are primary in the everyday life, but in a perfectly adaptive reaction they function complementary, and one or the other dominates depending on the situation.

Leaving aside the clinical-theoretical accounts of personality psychology, I will introduce briefly some more recent point of views, that are based more directly on the canon of interoception research.

Interoception research on well-being

The association between interoception and well-being is well discussed partly in Chapter 3, and mainly in Chapter 5. In the following I will provide a brief update only.

A recently published paper about interoception and health emphasizes the significance of interoceptive appraisal, defined as “the process of making sense of consciously detected physiological change” (N. A. Farb & Logie, 2018, p. 228). Even if one is not necessarily aware of the appraisal process itself, all the integrated physiological changes are conscious by definition. Of course, interoceptive accuracy is needed to provide physical information, but the perception itself does not have to be correct.

Some mental disorders can be interpreted as special cases of disturbances in interoceptive processes, and in some cases also as disturbances in emotion regulation. According to Paulus and Stein, for example, in depression, the perception of the interoceptive signals are down-regulated, while in anxiety interoceptive cues are overemphasized (Paulus & Stein, 2010). As we can see, this does not mean accurate perception, the mental disturbances are based on the subjective evaluation of the signals. Similarly, other theoretical works suggest that impaired interoceptive processes might play a significant role in addiction too (Paulus & Stewart, 2014; Verdejo-Garcia, Clark, & Dunn, 2012). This was also supported by empirical studies using breathing load (Stewart, Juavinett, May, Davenport, & Paulus, 2015).

6.7. Limitations

This thesis, just like any empirical work, has limitations. Most of these were listed above after each reported study, but I will summarize them here briefly, and also add some extra comments.

Before I do so, I would like to point out that according to the regulation of the Doctoral School of Psychology, ELTE Eötvös Loránd University, I am not allowed to change anything in the already published papers (Ch.2-5). Broadly speaking it is also a limitation of my thesis, as I am not able to adjust the inconsistency of the applied terminology, or to correct any later discovered mistakes.

All of the above presented four studies investigated samples of young, healthy university students. Although the similar samples make comparison of the findings more reliable, the conclusions that can be drawn are relatively limited. On the other hand, there was no systematic clinical interview prior to the measurements, so some participants might have mild physical or psychological disorder that influenced his or her answers or performance.

The number of the applied measures was relatively narrow, both concerning interoceptive sensibility and accuracy. Although the Body Awareness Questionnaire is a reliable and valid tool (Mehling et al., 2009), its status in the interception literature has been questioned by some the reviewers of our papers (Ferentzi, Drew, et al., 2018; Ferentzi et al., 2017), which reflects well the debate about the definition of interoceptive sensibility versus body awareness. The application of more than one questioner to assess interoceptive sensibility would have probably shift the focus from the terminological debates about body awareness. We have to point out, however, that none of the measures of interoceptive sensibility is fully accepted or in accordance with theoretical considerations. Some of them (Mehling et al., 2012; Porges, 1993) became relatively widely used, but they are also driven but strong theoretical assumptions, and accordingly, they do not focus on pure bodily sensations. I will add more to this issue below when I write about future directions of interoception research (see Ch.6.6).

Similarly, even if more interoceptive channels were assessed to investigate interoceptive accuracy than in most of the previous studies, the number is still relatively limited. Our choice was partly driven by theoretical, but also by practical considerations, such as availability of laboratory instruments.

6.8. Future directions

Methodological investigations

The research filed of interoception is getting more and more popular, and with this, the scope of the investigated topics becomes wider and wider. A number of new research areas has been introduced recently in interoception research, topics such as the Tourette syndrome (Ganos et al., 2015), suicidal behavior (Forrest, Smith, White, & Joiner, 2015), and addiction (Paulus & Stewart, 2014), just to mention a few.

As we saw above, the role that the perceived bodily signs might play in psychological functioning has a strong theoretical background (Carver & Scheier, 1981; Damasio, 1994, 2010; Seymour Epstein, 2014; Rogers, 1951, 1959). Therefore it is appealing to build a logical argument, that interception plays a significant role in almost any psychological function or disorder. This might or might not be, the case; however, the investigation of too many psychological phenomena might lead to findings that reflect false positive results. A good example is the investigation of autism, as the low level of interoceptive accuracy in autism spectrum disorder (Garfinkel, Tiley, et al., 2015; Quattrocki & Friston, 2014) turned out to be more associated with alexithymic feature of autism than with the disorder itself (Shah, Hall, Catmur, & Bird, 2016).

The systematic and theoretically well founded investigation of the methodology of interoceptive sensibility and accuracy is still missing. Most of the measures of interoceptive sensibility are strongly driven by theory or by a certain therapeutic approach (Daubenmier, 2005; Mehling et al., 2012; Miller et al., 1981; Porges, 1993), which influence the content of the items. The last review on the subject (the investigated phenomenon is called, however, ‘body awareness’ in the title) has been published ten years ago (Mehling et al., 2009). I as far as I know, there is no questionnaire that would systematically cover all the modalities of interoception. Although there are some assessments with a relatively wide range of items (Mehling et al., 2018, 2012; Porges, 1993), the investigated and selected topics are not supported by strong theoretical or literature background. This might partly be rooted in the nature of interoception, namely that is hard to make a complete list of all the interoceptive sensations.

The methodology of interoceptive accuracy is also problematic, but in a different way. As we saw above, the topic of heartbeat perception paradigms is relatively widely investigated (Brener & Ring, 2016; Clemens, 1984; Knapp et al., 1997; Pennebaker & Epstein, 1983; Pennebaker & Hoover, 1984; Ring & Brener, 1996, 2018; Ring et al., 1994; Windmann, Schonecke, Fröhlig, & Maldener, 1999; Zamariola, Maurage, Luminet, & Corneille, 2018), but there is still no consensus about the right method (see Ch.1.2); while different interoceptive tasks lead to different results within the same modality.

Areas with clinical significance are relatively widely studied (e.g. the water load test, see: Mimidis, 2007; van Dyck, 2015); the majority of the tests applied in clinical context (Fonyó, Hunyady, Kollai, Ligeti, & Szűcs, 2004), however, did not become part of the canon of the measures of interoception (I have mentioned some test-battery to assess the sensitivity of the skin above, see Ch.1.2). The systematic investigation of the available and possible measures of interoceptive accuracy is an enormous work. As a first step, a systematic literature review that summarizes and introduces the available measures to investigate the channels of interoceptive accuracy would be great contribution to the field.

Generally speaking, the systematic studies on methodological issues of interoception are underrepresented. In the recently published edited book that covers the current scientific knowledge on interoception, methodology as a problematic point is not really mentioned (Manos Tsakiris & De Preester, 2018). On the other hand, more than the quarter of the chapters are mainly about the philosophy of interoception (Colombetti & Harrison, 2018; Corcoran & Hohwy, 2018; De Preester, 2018; F de Vignemont, 2018; Leder, 2018). As a holder of an MA degree in philosophy, I am not intended to demote the significance of philosophical discussion. Additionally, I think it is great to see a scientific book that is open for interdisciplinary discussions with numerous scholars representing both psychology and philosophy. I think, however, that the emphasis on the theoretical significance of interoception has to be balanced with more systematic studies on the methodological issues.

Psychopathology and health

In November 2016, the Laureate Institute for Brain Research organized an international meeting for interoception experts to discuss the role of interoception in mental health. Their conclusion on the subject presented in a paper published in 2018 (Khalsa et al., 2018). One of their main conclusion regarding the future directions of interoception research was, that the empirical data to determine the role of interoception in mental health is still missing. The majority of the studies on interoception had a cross-sectional design, and therefore it is hard to determine how a certain level of interoception relates to (the development of) psychopathology. Also, studies investigating young and old samples are highly underrepresented.

Another recent paper on health and interoception called for studies with multiple and more comprehensive methods (as opposed to applying self-report and heartbeat monitoring only) (N. A. Farb & Logie, 2018), with the hope that novel paradigms will helpful to extend our knowledge about the role of manipulated awareness and appraisal in the processing of interoceptive signals.

6.9. Conclusions

According to the findings of the recent thesis, interoception is a relatively stable multidimensional and multimodal construct. Therefore, whenever interoception is investigated, it is highly advisable to emphasize what was the applied method. My recommendation would be not to use the term ‘interoception’ without a further word or description to specify the exact dimension or modality that has been assessed (e.g. interoceptive accuracy, interoceptive sensibility, cardiac interoception, gastric interoception).

Additionally, it would be highly advisable to examine more than one dimension and modality in the empirical studies of interoception. This would also prevent the misinterpretation of the results, and would be more informative regarding the phenomena. Even if only a certain sensory modality is relevant in the particular study, the usage of a (presumably) non-relevant interoceptive “control” modality is advisable.

The perception of the internal bodily information is considered to be relevant in various significant psychological phenomena. To understand their dynamics better, the empirical investigations have to take into account the multimodal and multidimensional nature of interoception.

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