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Knowing your Heart Reduces Emotion-Induced Time Dilation

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Abstract

Human timing and interoception are closely coupled. Thus, temporal illusions like, for example, emotion-induced time dilation, are profoundly affected by interoceptive processes. Emotion-induced time dilation refers to the effect when emotion, especially in the arousal dimension, leads to the systematic overestimation of intervals. The close relation to interoception became evident in previous studies which showed increased time dilation when participants focused on interoceptive signals. In the present study we show that individuals with particularly high interoceptive accuracy are able to shield their timing functions to some degree from interference by arousal. Participants performed a temporal bisection task with low-arousal and high-arousal stimuli, and subsequently reported their interoceptive accuracy via a questionnaire. A substantial arousal-induced time dilation effect was observed, which was negatively correlated with participants' interoceptive accuracy. Our findings support a pivotal role of interoception in temporal illusions, and are discussed in relation to neuropsychological accounts of interoception.

Keywords

Time perception, interoception, arousal, temporal bisection

1. Introduction

Accurate perception of time is one of the core abilities needed for organisms to survive. Thus, humans as well as many other species have remarkably accurate timing abilities, though we do not have a dedicated organ for perceiving the flow of time (Paton & Buonomano, 2018; Vatakis et al., 2018). While the exact

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mechanisms underlying human timing are still under debate (Kononowicz et al., 2018; Mella et al., 2019; Roseboom et al., 2019) there is converging evidence that interoception — that is, the awareness of one's own physiological states — is crucially involved in the processing of time. For example, Meissner and Wittmann (2011) showed that higher interoceptive accuracy is associated with higher temporal accuracy. Although heart rate does not directly affect time perception per se (see Schwarz et al., 2013), the sensitivity of one's own heartbeat seems to be connected to time perception (Meissner & Wittmann, 2011).

The close connection between timing and interoception, which is corroborated by accumulating neuroscientific evidence, is caused by both being processed in the insular cortex. Though there is not yet a particular brain structure attributed to time perception, pivotal cognitive processes are associated with the insular cortex (Bueti & Macaluso, 2011; Livesey et al., 2007; Tomasi et al., 2015). For example, in a duration reproduction task where participants learned, imitated, and then reproduced a given time interval, Wittmann et al. (2010) showed a linear increase in activation in the dorsal posterior insula during the encoding of to-be-reproduced time intervals. With regard to interoception, imaging studies propose the insula as being the critical substrate for the processing of interoceptive information (Schulz, 2016; Simmons et al., 2013).

However, the intimate entanglement between timing and interoception also becomes apparent in interoception's effect on temporal illusions. One of the most intensely investigated temporal illusions is emotion-induced dilation of time. Most current dimensional models of emotion conceive of individual emotions as being composed of a valence and arousal component (Bradley & Lang, 1994; Russell, 1980, 2003). In particular, the arousal component has well-established and substantial effects on human timing. For example, Droit-Volet et al. (2004) have shown that durations presented with an emotional face stimulus were overestimated relative to neutral face expressions (see also Angrilli et al., 1997; Droit-Volet & Meck, 2007; Fayolle et al., 2015; Mella et al., 2011; Noulhiane et al., 2007; for a review see Lake et al., 2016). This effect is commonly referred to as the time dilation effect.

A modulation of this effect by introspection was first demonstrated by Pollatos et al. (2014a). They found the emotion-induced time dilation effect to be increased when participants were instructed to focus on their interoception as opposed to focusing on external stimulation. The authors explained their findings by asserting that subjective time is affected by physiological states and how organisms perceive these changes in physiological states. When the individual's focus is on interoceptive signals, salience of these changes can activate (or deactivate) the sympathetic tone, which in turn leads to a more pronounced change in perceived time.

In another study that did not include an arousal component, Pollatos et al. (2014b) showed that accurate perception of heart beats was mediating accuracy of estimating time intervals. Similarly Cellini et al. (2015) showed that heart beat perception was associated with higher temporal sensitivity. In the present study we approach the relation between interoception and timing from an individual difference perspective. While a focus on interoception has been shown to intensify the effect (Pollatos et al., 2014a), individuals with a particularly accurate interoception might show a reduced time dilation effect. Such a hypothesis is supported by current theorizing about the detailed neuropsychological mechanisms of interoceptive processing.

Human interoception is commonly defined as experiencing the state of the body as a product of the central nervous system (Ceunen et al., 2016). It is typically conceived of as a multidimensional concept (Garfinkel et al., 2015) with accuracy of interoceptive perception, interoceptive sensibility (how sensitive one is regarding internal bodily changes) and interoceptive awareness (cognitive monitoring or the correspondence between one's actual interoceptive accuracy and personal judgment of accuracy). This experience, as Craig (2008) demonstrated, is a cross-modal integration of the central nervous system. Creating such a central representation is assumed to be a function of the insular cortex (Evrard, 2019). The dorsal posterior insula provides high-resolution homeostatic information to the mid-insula. The mid-insula also receives information from the secondary somatosensory cortex, enabling the integration of non-homeostatic input — salient emotional information from the environment via sensory inputs. Communicating also with the amygdala and hypothalamus, the mid-insula is the key locus for structuring interoception and an "integrated re-representation" (Craig, 2009). The processing of this re-representation in the right anterior insula enables conscious interoception (see Fig. 1). This homeostatic representation resembles live emotions that are ever-changing by context and creates an image of the self for the current moment. According to this model, there are storage units filled with these salient homeostatic representations — global emotional moments — that constitute the perceived passage of time. When these salient representations are generated with an increased rate, such as in highly aroused contexts, global emotional moments become filled more quickly and, thus, subjective time feels like it is standing still, or time dilates. When one focuses on these representations, such as in the Pollatos et al. (2014a) study, the dilating effects become more severe.

Yet, these combined internal representations are constantly matched against sensory input, and individuals seem to strongly differ in the quality and effectiveness of these sensory inputs. This has recently been conceptualized in a model by Ainley et al. (2016). This model is based on the free energy principle, which assumes that organisms aim to minimize the sum of differences between the actual sensory inputs by internal models (Friston, 2009). Interoception is also considered within the free energy principle because homeostatic information is bounded to the provided interoceptive output. The free energy principle assumes that the brain develops 'generative models' operating within predictive coding principles.

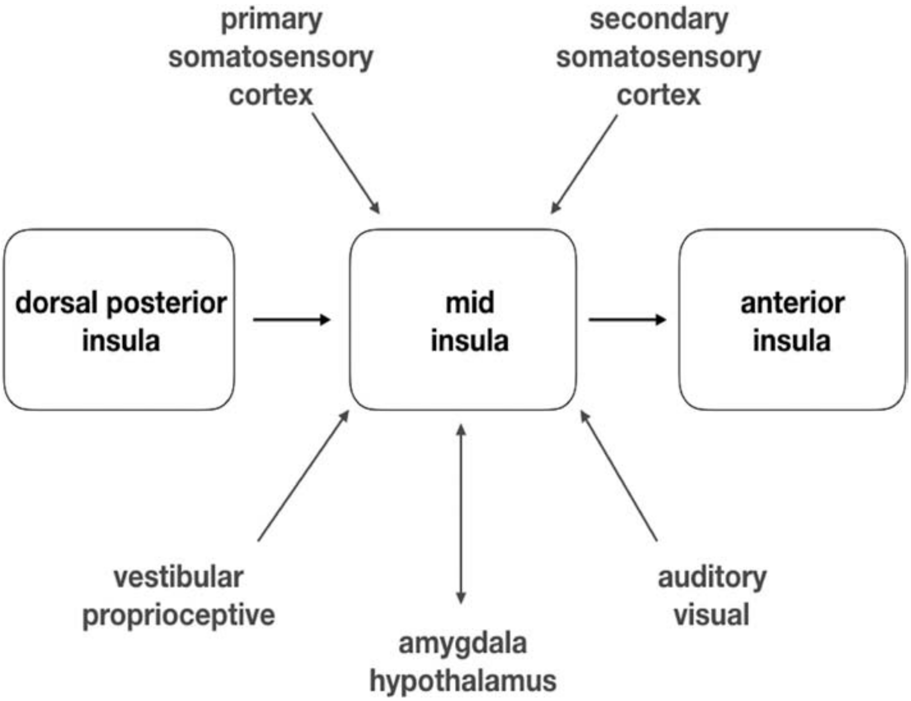

Figure 1. Posterior-to-anterior information progression for interoceptive representation. Double-headed arrows indicate dynamic communication between structures rather than only collecting input. Adapted from Craig (2008).

This model generates 'prior' predictions/beliefs about the sensory input that are kept updated by the portion of the input that is incompatible with the priors. This portion is termed the 'predictive error' (PE). Here, what constitutes our perception is achieving the minimal free energy (summation of all PEs) in order to reach as accurate as possible arepresentation of sensory input (see Fig. 2; Friston, 2009).

In the model by Ainley et al. (2016) the predictive coding account of interoception explains individual differences in interoceptive accuracy by generating more or less precise PEs. Interoceptive accuracy is generally measured by a heartbeat perception task where the ratio of counted heartbeats (for a certain period) to the actual number of heartbeats is compared. The model assumes that such a top-down modulation of attention works under the same principles in order to optimize free energy. Specifically, people with higher interoceptive accuracy perform more efficiently in Bayesian optimal updating of interoceptive PEs, whereas lower interoceptive accuracy leads to less frequent, less precise PEs, which implies attentional modulation is not successful in collecting interoceptive signals during heartbeat perception tasks. A less habitual salience of interoceptive signals is proposed to make people with lower interoceptive accuracy more susceptible to

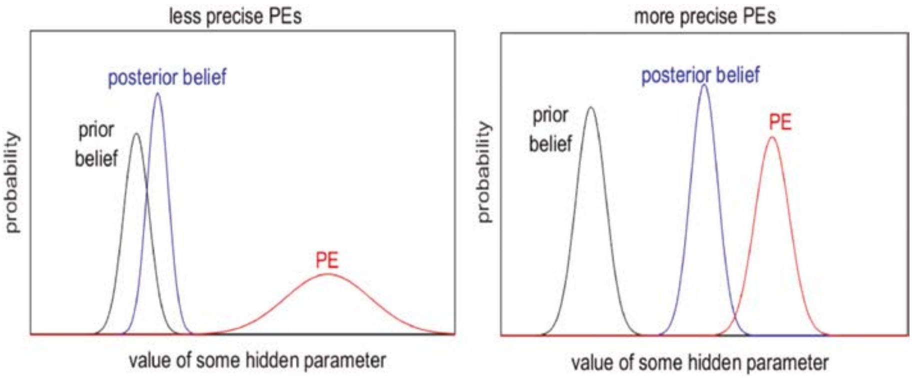

Figure 2. Graphical illustration showing how the precision of predictive error (PE) affects posterior beliefs to update prior beliefs. Probabilities refer to a hidden (unknown) parameter of the organism. The width of the distribution refers to relative dispersion or variance. Precision is the reverse of dispersion. The relative precision of PE is essential to update the prior belief to the posterior. When the relative precision of PE is higher (left figure), the posterior is shifted towards PE, whereas with lower precision (right figure), PE has a smaller effect on posterior belief (adapted from Adams et al., 2013).

illusory perception and deviant belief (Jiang et al., 2013). PEs during a heartbeat perception task are assumed to be reflected in dedicated structures in the cortex, presumably the anterior insula (Craig, 2009). Therefore, higher interoceptive accuracy leads to more effective updating of priors and, through time, more ready adaptation to altered heart-related parameters. On the contrary, lower interoceptive accuracy decreases the precision of PEs and leads to less informative priors, overall worsening the perception of own heartbeats.

From a time-perception perspective, we expected interoceptive accuracy to modulate how accurately we build temporal representations. With respect to the informativeness of priors and flexibility in changing different contexts, we reasoned that individual differences in interoception — measured by interoceptive accuracy — should modulate how much time dilates under arousal. With higher interoceptive accuracy, people should be more resistant to arousal-based changes — higher autonomic reactivity — and exhibit a weaker effect of arousal in their behavioral timing responses compared with individuals with lower interoceptive accuracy. Although arousal constantly leads to a faster loading of 'global emotional moments' (Craig, 2009), this is— at least for individuals with high interoceptive ability — constantly counteracted by high-quality PEs (Ainley et al., 2016).

In order to test this hypothesis, we accessed individuals' emotion-induced time dilation effects and measured their interoceptive ability. Our study concerns the behavioral accuracy dimension of interoceptive performance. Although it is important to conceptually differentiate between other aspects of interoception, interoceptive awareness and interoceptive sensibility have recently been reported to correlate to interoceptive accuracy to different extents (Garfinkel et al., 2015). We expected mainly that accuracy would be associated with behavioral timing parameters because it is proposed as contributing corrective PEs to interoception and, thus, potentially reducing emotionally induced illusions. For explorative reasons, we also measured awareness and sensibility to replicate the three-dimensional model of Garfinkel et al. (2015) and to test these dimensions' possible associations with time dilation.

2. Methods

2.1. Participants

Twenty-six students were recruited via SONA, the online recruiting system of the University of Freiburg. The exclusion criteria were hearing impairment, use of psychotropic drugs or antiallergics during the past two months, any psychiatric diagnosis, and any cardiovascular conditions. Participants gave their informed consent and received course credits. One participant was later excluded due to reporting a congenital heart disease after the testing session. The final sample consisted of 25 participants ($M = 23.72$ years, SD = 5.07, 6 male, 24 right-handed).

2.2. Procedure

The participants were asked to mute their cellphones and portable devices, and not to wear any watches. After a short introduction and an overview of the procedure to follow, participants gave their informed consent. Afterwards, they filled out a body perception questionnaire as a measure of interoceptive sensibility (see below for details). Then, three electrocardiogram (ECG) electrodes were placed on their torsos, forming Einthoven's triangle (one on the left upper chest, one on the right upper chest and one on the right rib) in preparation for cardiac recording. Next, participants performed a proprioception task on a tablet PC and stated their confidence about their responses (see Supplementary Text S1 for proprioception task description and results). The ECG electrodes were connected to a heart activity recording system and, as a measure of interoceptive accuracy, the participants performed the heartbeat perception task and rated their confidence using paper and pencil. Finally, participants performed a temporal bisection task. The procedure took between 75 and 90 minutes to complete.

2.2.1. Body Perception Questionnaire

One subtest, covering 'awareness', of the original body perception questionnaire by Porges (1993) was completed by the participants. The participants rated their awareness of their body processes in 45 items (e.g., "During most situations, I am aware of how fast I am breathing".) The scales' gradations were anchored as 0 (Never), 1 (Occasionally), 2 (Sometimes), 3 (Usually), and 4 (Always). The

German version of this subtest was filled out by the participant using pencil and paper (see Note 1).

2.2.2. *Heartbeat Perception Task*

Three pre-gelled, self-adhesive ECG electrodes were positioned on the participants' chests and were connected via leads to the BIOPAC MP160 System with an ECG100 amplifier (physiological measurement tool; BIOPAC, Goleta, CA, USA). Heart activity was recorded using ACQknowledge 5.0 (analysis software tool; BIOPAC). Participants were instructed to sit upright, with hands on their thighs and their eyes closed. They were told not to move or to speak during the recording. They were instructed to silently count their heartbeats, to concentrate on their heart beating, and to count by feeling their body and without the use of any manual techniques. The heartbeats were recorded for durations of 15, 30, 45, and 60 s. Each participant was tested for each of the durations. The order of the test durations was varied for every participant by Latin square counterbalancing. After reporting the number of heartbeats, participants rated their belief about how much the reported number of heartbeats matched the recorded number of heartbeats using pencil and paper on a visual analog scale from 0 to 100. At no time did participants receive any feedback on their performance during the experiment. After the heartbeat perception task, the ECG electrodes were removed from the participants' chests.

2.2.3. *Temporal Bisection Task*

For the execution of the temporal bisection task, E-Prime software 2.0 (Psychology Software Tools, Sharpsburg, PA, USA) was used on a 24-inch (144 Hz) PC screen with a resolution of 2560 × 1440. During the task, participants wore headphones. The task involved two phases: a learning phase and a testing phase. During the learning phase, participants learned a short (900 ms) and a long (3450 ms) anchor duration. A 100 × 100 blue square pixel represented the target stimuli. After each presentation feedback occurred on screen which informed participants which of the anchors was just presented (e.g., this was the short/long anchor duration). The presentation order of the anchor durations was randomized. After the learning phase, participants were exposed to several different comparison durations. The comparison durations varied randomly between seven durations that were logarithmically spaced between anchor durations (900, 1125, 1400, 1750, 2200, 2750, and 3450 ms). In each trial, participants judged whether the comparison duration was closer to the short or the long anchor duration by pressing the X or M keys, respectively (see Fig. 3 for further details on the trial sequence). Participants were instructed to refrain from counting. They received no feedback on their responses. Simultaneous to the presentation of the blue squares, one of two sounds was played through the headphones. Presentation of the sounds lasted equally to the duration of the blue square. The sounds, originating from the International Affective Digitized Sound system (Bradley & Lang, 2007) induced high or low arousal

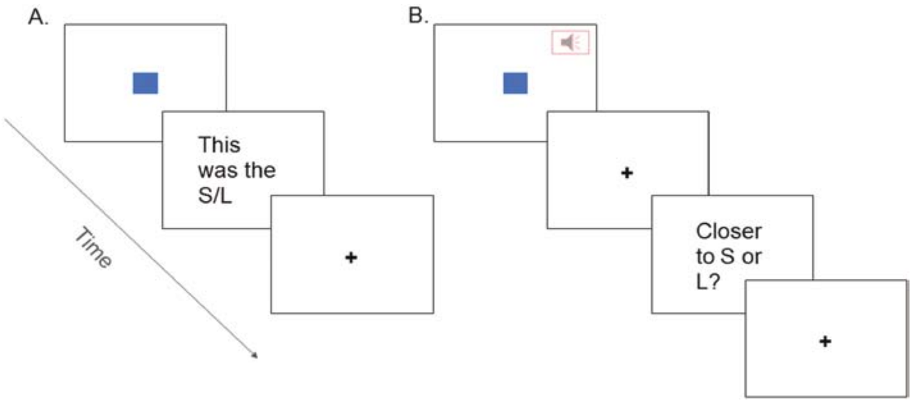

Figure 3. (A) The trial sequence of the learning phase. (B) The trial sequence of the testing phase.

while being neutral in valence. High arousal was induced by a ringing tone (identified as number 704 in the database) and low arousal was induced by a tone of rain (number 698). It was deemed appropriate only to choose tones that do not repeat a perceptible rhythm to avoid giving indices about time duration due to repetition. Participants were instructed not to focus on the tones but on the blue square.

Each participant completed 30 trials per comparison duration, for a total of 210 trials (105 for each arousal condition) in the testing phase. Comparison durations and arousal stimuli were randomly presented in both blocks. There was a three-minute break after the first half of the trials. After the break, participants were reminded of the two anchor durations and continued the testing as before. In total, the task lasted for 40 minutes on average.

2.3. Data Analysis

2.3.1. Body Perception Questionnaire

The body perception questionnaire contained 45 items, each with five response options (Porges, 1993). These response options were coded from zero (never) to four (always) and added up across all items. Consequently, the minimum attainable score (low sensitivity for internal bodily functions) was 0 points and the maximum attainable score (high sensitivity for internal bodily functions) was 180 points.

2.3.2. Heartbeat Perception Task

The participants' reported number of heartbeats (reported heartbeat) was noted for each trial. Recorded heartbeats per test duration were documented. Subsequently, the heartbeat perception score was calculated:

$$1-\frac{1}{4}\sum_{n=1}^{4}\frac{|\text{actualheartbeat} - \text{reportedheartbeat}|}{\text{actualheartbeat}} \tag{1}$$

Here n represents the testing durations; 15, 30, 45, and 60 ms. A large difference between the reported and the actual heartbeat would be evidence of low interoceptive accuracy.

The participants' beliefs about the exactness of the match between their reported and actual heartbeats (interoceptive confidence) were measured via a visual analog scale. Participants could reach a minimum score of zero, meaning that they expected the maximum difference between the number of reported and actual heartbeats. A maximum score of one, however, represented the belief of perfect matching between the number of reported and actual heartbeats. The interoceptive accuracy and interoceptive confidence were used to calculate interoceptive awareness (n stands for the testing durations):

A low interoceptive awareness score represents a severe misjudgment of one's heartbeat task performance.

$$1-\frac{1}{4}\sum_{n=1}^{4}(|\text{interoceptiveaccuracy} - \text{interoceptiveconfidence}|) \tag{2}$$

2.3.3. Temporal Bisection Task

A cumulative Gaussian function was fitted to every participant's mean proportion of 'long' responses across different duration spans, separately for the arousing and non-arousing condition (Çoşkun et al., 2015). The mean R-squared for individual fits were 93.6 and 93.9 for low- and high-arousal stimuli, respectively. A point of subjective equality (PSE) was allocated where the probability of the participant believing the given duration to be long was 0.5. The PSE marked where the participant could not discriminate whether a comparison duration was closer to the long or the short anchor. The fitting of a psychometric function for each different arousal condition led to two PSEs for every participant. The extent of deviation between the PSEs of the low-arousal and the high-arousal conditions functioned as a measure of the individual extent of the time dilation illusion. To compute this shift, PSE of the high-arousal condition was subtracted from the PSE of the low-arousal condition, per participant (for an alternative way of calculating accuracy change see Grondin et al., 2015; Kopec & Brody, 2010; Penney and Cheng, 2018). To clarify whether the PSEs differed significantly over participants, a paired-sample t-test was performed on the low- and high-arousal PSEs. A significant leftward shift of the psychometric function, meaning the PSE of the high-arousal condition to decrease when compared with the PSE of low arousal, would reveal a time dilation effect.

3. Results

Figure 4 shows the proportion of 'long' responses for two stimuli of different arousal levels. We have compared PSE values of high- and low-arousal conditions

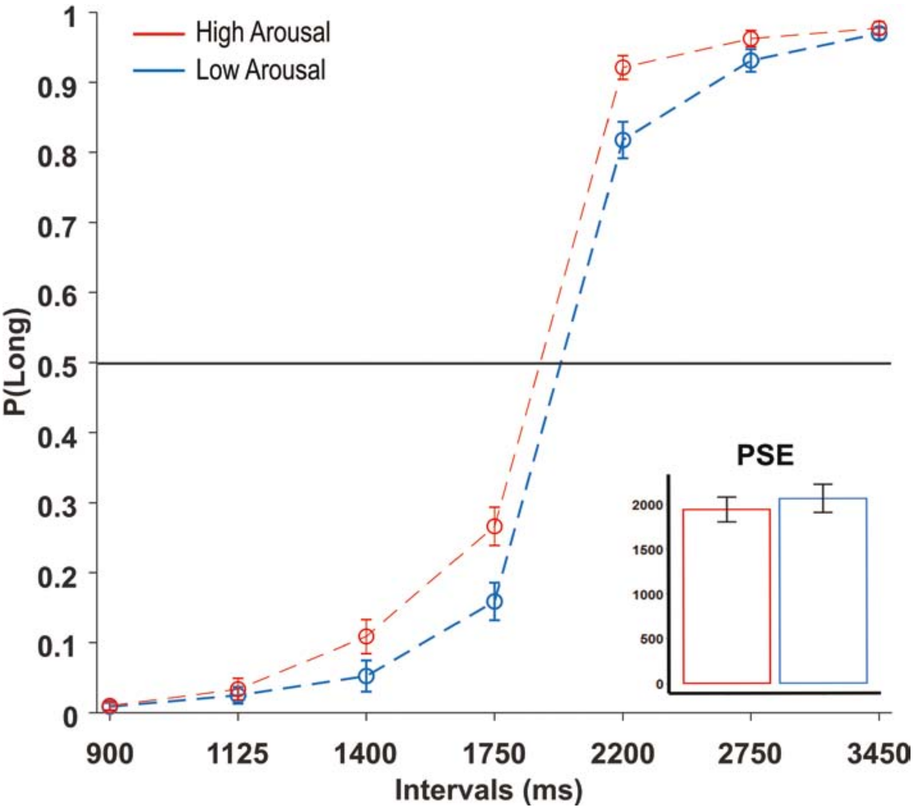

Figure 4. The proportion of 'long' responses plotted against comparison durations for high- and low-arousal stimuli. Whiskers around data points on the lines stand for standard error. Bar plot shows average of individual point of subjective equality (PSE) values obtained via cumulative Gaussian fits, per arousal level. Whiskers stand for standard deviation.

(Table 1). In line with the hypothesis, a paired-sample t-test revealed the shift to be significant [$t(24) = 6.83$; $p < 0.001$; $d = 1.37$; Bayes factor (BF) = 36526]. The sample did show the time dilation effect — the overestimation of time due to the arousing condition — and thus enabled the correlative investigation between the perception of time and interoception.

Following the presumption that time-perception performance and interoception are positively related, one-tailed significance tests on correlations were calculated between the bisection point shift and the interoceptive variables (Table 2). Correction of False-Discovery Rate was planned for multiple comparison corrections. The individual shifts in PSEs did not significantly correlate with the interoceptive sensibility ($r = 0.25$; $p = 0.117$; BF < 1) or the interoceptive awareness ($r = -0.27$; $p = 0.096$; BF < 1). A significant connection was detected between the shift in PSE and interoceptive accuracy ($r = -0.38$; $p = 0.028$; $R^2 = 0.14$; BF = 3.54) — the exactness of truthfully feeling one's heartbeat (Fig. 5). The perception

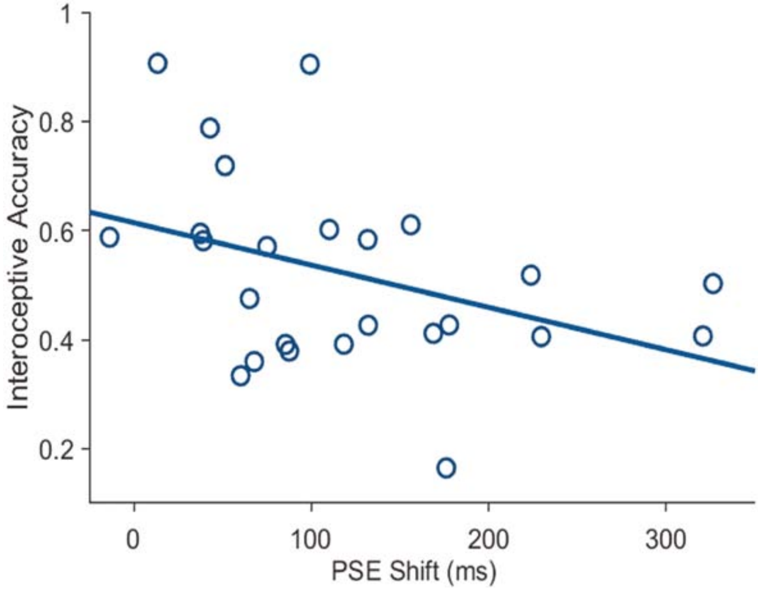

Figure 5. Correlation between interoceptive accuracy and time dilation effect shown as the point of subjective equality (PSE) shift.

of time appeared not to be related to the subject's sensibility of interoception or the awareness of one's own performance on heartbeat detection.

Moreover, intra-interoceptive correlations between the three components of interoception were analyzed. No statistically significant correlation was found between any of the interoceptive variables (all $p > 0.05$; BF < 1).

4. Discussion

In this study, we investigated how individual differences in interoceptive accuracy, interoceptive awareness, and interoceptive sensibility are related to time dilation. We measured interoceptive sensibility with a body awareness questionnaire, interoceptive accuracy with a heartbeat perception task, and interoceptive awareness based on confidence judgments during the heartbeat perception task. To induce a time dilation effect, we employed a temporal bisection task with stimuli, including two levels of arousal. We compared the association between response characteristics obtained from the bisection task and interoception measures. Replicating previous studies of time dilation, a highly arousing stimulus led to an earlier PSE relative to a lower-arousal stimulus (Droit-Volet et al., 2004).

In line with our hypothesis, higher interoceptive accuracy yielded smaller deviations in the PSE from low- to high-arousal stimuli. Higher interoceptive accuracy is assumed to indicate a better, more accurate understanding of the physiological state of the body, creating more precise information for generating internal models of the current physiological state. Our findings suggest that this increased precision enables an overall more accurate perception of sensory input. In line with Ainley et al. (2016), we assume that this is achieved by more precise error signals.

We reasoned that if higher interoceptive accuracy is a sign of a more realistic perception of sensory input and more optimal accumulation of PEs, the opposite of this characteristic (lower interoceptive accuracy) should indicate perceptual representations that are more vulnerable in changing environments. Similarly for time perception, more effective PEs and higher autonomic reactivity enable more accurate temporal representations which are, in arousing contexts, distorted to a lesser extent.

As we mentioned in the introduction, studies suggest a role for the dorsal posterior insula both in interoceptive processes and time perception. Findings showing a correlation between temporal accuracy and heartbeat perception scores (Meissner & Wittmann, 2011), suggesting more accurate timing behavior for higher interoceptive accuracy are well in line with the present findings on time dilation. In addition, our results support a view of interoception as a complex multidimensional concept. Only interoceptive accuracy correlated with time dilation. Yet, the monitoring of heartbeat perception performance was not associated with the timing parameter. The absence of this correlation suggests that, while tracking the physiological state of the body is linked with timing and insular activity, metacognitively assessing this tracking is not part of this link. We also found that none of the interoceptive dimensions correlated with each other. These findings are in line with the three-dimensional model of interoception of Garfinkel et al. (2015). We recommend that future studies on timing and interoception carefully differentiate between the three dimensions because they can have clearly different influences on temporal illusions.

However, our study was limited to a specific temporal illusion: namely, the emotion-induced dilation of time. It is not clear yet which role interoception plays in other temporal illusions like, for example, intentional binding (Haggard et al., 2002; Ruess et al., 2017, 2018) or chronostasis (Morrone et al., 2005; Yarrow, 2010; Yarrow et al., 2001), and the temporal oddball effect (Ulrich & Bausenhart, 2019). Future studies could test whether inter-individual differences in interoception have similar effects on these temporal illusions, and whether such potential effects are also bound to the accuracy dimension of interoception.

When it comes to the perception of self-related signals, anxiety and depression are two important conditions to consider. Several neuroimaging studies show increased insular activity in depressive or anxiety symptoms (such as self-guilt, worry or sadness), or in clinical depression and anxiety. In both disorders people's internal state is altered (due to negative self-perception or attentional bias — worry) which is the base for interoceptive output (Paulus & Stein, 2010). Previous research on interoceptive accuracy have shown a positive correlation for anxiety, and a negative correlation for depression (Pollatos et al., 2009). Rather than the overall disorder, Dunn et al. (2010) have shown that anxiety-specific arousal is associated with accuracy, and this association becomes weaker as the anhedonia symptom gets more severe. In addition to the arousal manipulation as in our experiment, symptoms of anxiety and depression, especially anxiety-specific arousal, should be carefully considered to explain time dilation in different groups.

We have not found a meaningful relationship between interoceptive sensibility and time dilation or with the other interoceptive measures. These findings should be interpreted while keeping in mind that the German version of this questionnaire is not yet validated and the current version might not be robust enough to represent interoceptive sensibility.

In sum, we investigated interoception — specifically interoceptive accuracy — to understand a well-known timing phenomenon: emotion-induced dilation of time. We explained individual differences in interoceptive abilities within the predictive coding framework, proposing that building temporal representation in changing contexts depends on how well we can process errors in our predictions. As we hypothesized, interoceptive accuracy was associated with the magnitude of time dilation, suggesting interoceptive input signals of higher quality enable less deviant, less illusory perceptions of time. Future studies should test this effect with respect to different time ranges and other temporal illusions. The findings of this study support the three-dimensional model of interoception; however, each aspect of interoception needs a more detailed investigation regarding their relation to subjective time.

Table 1.
Mean PSE values per arousal condition.

Condition	Mean	SD
Low arousal	2058.09	159.21
High arousal	1938.76	137.23

Table 2.
Mean and standard deviation values of interoceptive measures.

Measure	Mean	SD
Interoceptive accuracy	0.52	0.03
Interoceptive awareness	0.77	0.02
Interoceptive sensibility	98.84	5.44

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Supplementary Material

Supplementary material is available online at:
https://doi.org/10.6084/m9.figshare.12417203

Note

1. During several pilot studies it turned out that two items were frequently misunderstood, probably due to regional differences in the semantics of some less common words. We slightly changed the wording in two items without changing the content:
   Item 19. Gänsehaut (English: goose bumps; original: Hühnerhaut)
   Item 20. Ein Gefühl von eingeschlafenen Gliedmaßen (English: numbness; Taubheit, Ameisenlaufen) (original: Ameisenlaufen oder Kitzeln oder Einschlafen (gefühllos) im Körper)

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