



# Suppression of the auditory N1-component for heartbeat-related sounds reflects interoceptive predictive coding

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## ABSTRACT

Although many studies have elucidated the neurocognitive mechanisms supporting the processing of externally generated sensory signals, less is known about the processing of interoceptive signals related to the viscera. Drawing a parallel with research on agency and the perception of self-generated action effects, in the present EEG study we report a reduced auditory N1 component when participants listened to heartbeat-related sounds compared to externally generated sounds. The auditory suppression for heartbeat sounds was robust and persisted after controlling for ECG-related artifacts, the number of trials involved and the phase of the cardiac cycle. In addition, the auditory N1 suppression for heartbeat-related sounds had a comparable scalp distribution as the N1 suppression observed for actively generated sounds. This finding indicates that the brain automatically differentiates between heartbeat-related and externally generated sounds through a process of sensory suppression, suggesting that a comparable predictive mechanism may underlie the processing of heartbeat and action-related information. Extending recent behavioral data about cardio-visual integration, the present cardio-auditory EEG data reveal that the processing of sounds in auditory cortex is systematically modulated by an interoceptive cardiac signal. The findings are discussed with respect to theories of interoceptive awareness, emotion, predictive coding, and their relevance to bodily self-consciousness.

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## 1. Introduction

Recent findings from neuroscience and psychology have underlined the central role of the processing of bodily signals for a neurobiological model of the self. It has been found for instance that in neurological patients disturbed processes of multisensory integration can result in altered perceptions of the body and the self (Blanke, Landis, Spinelli, & Seeck, 2004; Heydrich & Blanke, 2013a; Heydrich, Dieguez, Grunwald, Seeck, & Blanke, 2010). Furthermore, experimentally induced multisensory conflicts can result in illusory body perception and corresponding alterations in the bodily self (Aspell, Lavanchy, Lenggenhager, & Blanke, 2010; Ehrsson, Holmes, & Passingham, 2005; Lenggenhager, Tadi, Metzinger, & Blanke, 2007). Whereas many studies have focused on the importance of exteroceptive signals related to the body (e.g. vision and

touch), more recently it has been argued that interoceptive signals (i.e. signals related to internal bodily states and especially the viscera; cf. Critchley, Wiens, Rotshtein, Ohman, & Dolan, 2004) play an important role for the self as well (Aspell et al., 2013; Craig, 2002; Damasio, 2000). In the present study we draw a parallel between studies on the neurocognitive mechanisms underlying bodily self-consciousness (i.e. feeling of body ownership and agency) on the one hand (Blanke, 2012; Blanke & Metzinger, 2009) and studies on interoceptive awareness on the other hand (Craig, 2003; Critchley et al., 2004). That is, we hypothesize that the brain automatically processes and integrates interoceptive bodily signals with other sensory signals related to bodily self-consciousness.

Two key aspects of bodily self-consciousness are the ‘sense of body ownership’ (i.e. the sense that the body is mine) and the ‘sense of agency’ (i.e. the sense that I am the initiator of my actions; cf. Gallagher, 2000). According to the notion of predictive coding, the sense of agency relies on the successful integration of predicted and observed action effects (Blakemore, Wolpert, & Frith, 2000; Friston, 2012; von Holst & Mittelstaedt, 1971). Each of our

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actions is accompanied by efference copy signals of the descending motor command that are used by the brain to anticipate the sensory consequences of our movements and to distinguish self-generated from externally generated action-effects (Wolpert, 1997). A classical way to study agency and predictive signals is to introduce visuo-spatial or temporal deviations between observed and actual movements (Fournier et al., 1998; Franck et al., 2001; van den Bos & Jeannerod, 2002). Typically, the feeling of agency decreases with increased visuo-spatial or temporal mismatches between performed and observed movements and this holds both for movements performed with the upper limbs and the lower limbs (Acosta & Pegalajar, 2003; Fournier et al., 1998; Kannape & Blanke, 2013; Kannape, Schwabe, Tadi, & Blanke, 2010; van den Bos & Jeannerod, 2002).

Of interest for the present study, the anticipation of one's movement consequences has been associated with sensory suppression or attenuation for self-generated action effects. For instance, predictable self-generated touches are perceived as less intense than self-generated touches that were unpredictable due to a temporal delay between the movement and the felt touch (Blakemore, Wolpert, & Frith, 1998; Weiskrantz & Zhang, 1987) and are associated with reduced activation in somatosensory areas (Blakemore et al., 1998). Similarly, self-generated sounds and self-generated light flashes are perceived as less intense and are associated with reduced activation in respectively the auditory and the visual cortex (for review, see: Hughes, Desantis, & Waszak, 2013; Hughes & Waszak, 2011). In all these cases, based on corollary signals the brain anticipates the sensory consequences of own actions, which results in attenuated sensory processing and activation and allows one to distinguish self-generated from externally generated stimuli.

A reliable electrophysiological marker of sensory suppression in the auditory domain is the reduction of the auditory N1 component in the EEG that is typically observed in association with the processing of self-generated compared to externally generated sounds (Baess, Horvath, Jacobsen, & Schroger, 2011; Bass, Jacobsen, & Schroger, 2008; Chen et al., 2012; Gentsch, Kathmann, & Schutz-Bosbach, 2012; Gentsch & Schutz-Bosbach, 2011; Horvath, Maess, Baess, & Toth, 2012; Martikainen, Kaneko, & Hari, 2005; Sowman, Kuusik, & Johnson, 2012; Stekelenburg & Vroomen, 2012). Previous studies have suggested that the auditory N1 component originates from the primary auditory cortex/Heschl's gyrus (Godey, Schwartz, de Graaf, Chauvel, & Liegeois-Chauvel, 2001; Huottilainen et al., 1998; Mulert et al., 2005) and that the suppression of the N1-amplitude for self-generated sounds may reflect a modulation of the auditory cortex related to efference copy or prediction signals originating from motor and premotor areas (Aliu, Houde, & Nagarajan, 2009; Baess, Widmann, Roye, Schroger, & Jacobsen, 2009). N1 suppression has been observed for self-generated natural sounds compared to pitch-shifted speech sounds (Chen et al., 2012; Martikainen et al., 2005) as well as for simple auditory stimuli following a button press response (Baess et al., 2011; Bass et al., 2008). Based on these findings it has also been proposed that such sensory suppression for self-generated sounds is related to the sense of agency (Gentsch et al., 2012).

Whereas, studies on agency and body ownership have typically focused on exteroceptive sensory processing, less attention has been paid to interoceptive signals (but see: Aspell et al., 2013; see Discussion; Suzuki, Garfinkel, Critchley, & Seth, 2013). Interoceptive sensitivity refers to the ability to monitor our internal bodily states, such as hunger, thirst, and heart rate based on visceral signals. A specific instance of interoceptive sensitivity is the ability to monitor one's own heart rate or heartbeats. In the 1960s, researchers started to investigate individual differences in heart rate perception (e.g. for review see Carroll, 1977; Jones, 1994). The topic of heart rate perception received particular interest because

of its potential for biofeedback training (Whitehead, Drescher, Heiman, & Blackwell, 1977) and its presumed relation with emotional processing (Ferguson & Katkin, 1996; Wiens, 2005) and psychopathology (Ehlers & Breuer, 1992, 1996; Pollatos, Traut-Mattausch, & Schandry, 2009; Van der Does, Antony, Ehlers, & Barsky, 2000).

Different methods have been used to assess people's ability to perceive their own heartbeat. In the *heartbeat tracking task* (also known as the heartbeat counting task) participants are required to count their heartbeats during brief fixed intervals of various periods of time (Dale & Anderson, 1978; Schandry, 1981). The subjective estimation is then compared to the actual number of heartbeats for each time period, allowing to calculate a mean sensitivity index. Whereas in the *heartbeat tracking task* attention is directly focused on interoceptive signals, it has been argued that in the *heartbeat detection task* attention is focused more strongly on external sensory signals (Schulz, Lass-Hennemann, Sutterlin, Schachinger, & Voge, 2013). More specifically, in the *heartbeat detection task* (also known as the simultaneity paradigm) participants are required to indicate whether heartbeat sensations are simultaneous with externally presented stimuli, such as lights or sounds that are presented with different time delays following the onset of myocardial contraction (Brener, Liu, & Ring, 1993; Critchley et al., 2004; Davis, Langer, Sutterer, Gelling, & Marlin, 1986; Katkin, Morell, Goldband, Bernstein, & Wise, 1982; Whitehead et al., 1977; Yates, Jones, Marie, & Hogben, 1985). In the Method of Constant Stimuli sounds are presented at different intervals with respect to the R-wave, ranging in 100-ms steps from 0 to 500 ms (Brener et al., 1993; Schneider, Ring, & Katkin, 1998). For each of the different conditions participants are required to indicate whether they think the sound presented was simultaneous with their heartbeat or not. For each participant it is then determined whether the observed distribution of responses differs from chance and based on their ratings participants are classified as 'good' or 'bad' perceivers (Ring & Brener, 1992; Wiens, Mezzacappa, & Katkin, 2000).

In the present study we hypothesized that a similar mechanism of sensory suppression as observed for self-generated actions could underlie the perception of 'self-generated' sounds linked to the own heartbeat. That is, we speculate that the brain uses visceral and/or peripheral sensory signals to differentiate sounds that are presented in synchrony with one's heart compared to sounds that are presented asynchronously with one's heartbeat or to sounds that are externally generated, which should be reflected in a reduced N1 component for sounds in synchrony to one's heartbeat. To test our hypothesis we recorded participants' EEG and ECG while they were listening to sounds presented synchronously or asynchronously with their heartbeat. A similar approach to manipulate the synchrony of heartbeat-related sounds has been used in studies on heartbeat perception (Brener et al., 1993; Davis et al., 1986; Katkin et al., 1982; Whitehead et al., 1977; Yates et al., 1985) and in agency studies in which different temporal delays are typically introduced between one's action and the effects (Blakemore et al., 1998). Here, we expected to observe a suppression of the auditory N1 component for sounds presented in synchrony with one's heartbeat compared to asynchronously (i.e. delayed with respect to the onset of the R-wave) or to externally presented sounds (i.e. unrelated to the heartbeat). Moreover, by including different intervals between the heartbeat and the sound (Brener et al., 1993; Schneider et al., 1998) we investigated if a longer delay between one's heartbeat and the sound would be reflected in differential suppression patterns. Based on the finding that sounds presented at intermediate intervals (i.e. 200 and 300 ms) are most often perceived to be in synchrony with one's heartbeat (Brener & Kluitse, 1988), we expected the strongest effects of sensory suppression for these intervals and less for tones presented at 0 and 500 ms. Finally, we were interested whether the individual ability in heartbeat detection would

be related to a differential suppression of the auditory N1 component (e.g. stronger suppression for good heartbeat perceivers).

## 2. Methods

### 2.1. Participants

In total 15 right-handed subjects participated in the experiment (5 females, mean age = 24.6 years), all students at the École Polytechnique Fédérale de Lausanne, Switzerland. One participant was excluded because of excessive ocular movements contaminating the EEG signal, leaving 14 participants for the final EEG analysis.<sup>1</sup> All participants gave written informed consent before participation and received 50 CHF for participation. The experiment was approved by the local ethics committee and conducted in accordance with the guidelines from the Declaration of Helsinki.

### 2.2. Experimental setup and procedure

At the beginning of the experiment the EEG and ECG electrodes were applied and the participant was given a headphone for the presentation of the sounds. During the *heartbeat-interval conditions* and the *external-sound conditions* participants were instructed that sounds would be presented that could or not correspond to their heartbeat. It was explained that in some cases the sounds could be based on the ECG signal, while in other cases the ECG signal would be modulated by the computer to present the sounds with a certain delay. The participant's task was to indicate at the end of each block of auditory stimulation whether they believed the sounds corresponded to their heartbeats or not by using a forced-choice yes/no response. None of the participants reported suspicion regarding the experimental manipulation and all believed that the computer was able to detect their heartbeat online to generate auditory stimuli. During the *active-sound conditions* participants were instructed to press a button with their right index finger approximately every second and to listen to the sounds generated in association with the button press. During the *baseline condition* no sounds were presented and participants were instructed to sit still. During all blocks participants were instructed to keep their eyes open and to fixate on a white fixation cross that was placed approximately 150 cm in front of them, in order to minimize eye-movement-related artifacts in the EEG recording.

During the *heartbeat interval conditions*, an online detection algorithm was used to determine the onset of the R-wave and to generate auditory stimuli. Raw ECG data was acquired by placing two ECG electrodes on the participants' chest and the amplified ECG signal was sent through a BioSemi amplifier to the experimental computer at a sampling rate of 2048 Hz. Custom-made software computed at 60 Hz the instantaneous derivative of the signal (buffered data) to detect the high jump between Q and R (typical for the QRS complex). Continuous adjustment of the algorithm to cumulatively averaged extremes allowed for an automatic adaptation to inter-individual differences and signal amplitude variations. To guarantee optimal detection accuracy, the signal and the triggers were monitored during the placement of the electrodes in order to find their optimal position on the chest (highest QRS). An R-peak was detected when delta was larger than 20 to 30% of the Q-to-R difference (threshold was adjusted for each individual subject). The software, using Open Graphics Library, was able to present an auditory stimulus immediately after the detection of the R-peak (with a constant delay of 1 frame, due to the sampling rate: 33 ms) or at a pre-specified delay (i.e. 0, 100, 200, 300, 400 or 500 ms). In association with the presentation of the auditory stimulus a trigger was sent to the EEG computer, which allowed determining offline for each trial whether the online detection of the onset of the R-wave was correct.

In total the experiment consisted of 9 experimental blocks: 6 blocks in which the sounds were presented in association with the heartbeat at different intervals (*heartbeat-interval conditions*), 1 block in which the sounds were externally generated by the experimental computer (*external-sound condition*), 1 block in which the sounds were generated by a button press response by the participant (*active-sound condition*) and 1 block in which no auditory stimuli were presented (*baseline condition*). Each block took 240 s and block order was counterbalanced between participants. Auditory stimuli always consisted of a 100 ms 1000 Hz sine wave tone that was presented via a pair of closed headphones.

For the *heartbeat-interval conditions*, the interval between the onset of the heartbeat and the presentation of the auditory stimulus was manipulated in 100 ms steps. In total 6 different intervals between the R-wave and the auditory stimuli were used: 0 ms, 100 ms, 200 ms, 300 ms, 400 ms and 500 ms. The selection of these intervals was based on classical studies using the Method of Constant Stimuli (Brener et al., 1993; Yates et al., 1985), that has been used to investigate individual differences in the ability to detect one's heartbeat. Each interval condition was presented for a continuous period of 240 s, after which the participant was required to indicate whether the sounds corresponded to his heartbeat or not. A continuous interval of 240 s per condition was used rather than using shorter intervals, because adjusting the delay for each new condition required considerable time and effort. Switching more often

between conditions to have shorter blocks would have made the experiment too lengthy.

In addition to the different heartbeat-interval conditions, an *external-sound condition* was included in which the sounds were externally generated by the computer. More specifically, in the *external-sound condition* sounds were presented with a jittered interval of  $900 \pm 200$  ms. This interval was chosen a priori to resemble the average heart rate of the population of approximately 67 bpm, while at the same time introducing some natural variation in the presentation of the tones. In this way the control condition matched the heartbeat conditions as closely as possible in terms of frequency of stimulation, while the sounds were not systematically related to the heartbeat.

In the *active-sound condition* participants were required to press a button on a PST serial response box approximately every second and in association with each button press the same sound as used in the other experimental conditions was presented. The presentation of the sounds continued until 240 button press responses had been made (i.e. corresponding to the presentation of 240 sounds). In analogy to the presentation of the sounds in the *external-sound* and the *active-sound condition*, triggers were sent to the EEG computer to be stored for offline analysis.

In a *baseline condition* no auditory stimuli were presented and participants' EEG and ECG was recorded while they were sitting passively for 240 s. The rationale for including a baseline condition was to obtain a reliable marker of any effects in the EEG signal that were specifically related to the heartbeat (i.e. ECG-related artifacts and/or the heartbeat evoked potential; see: Fukushima, Terasawa, & Umeda, 2011; Gray et al., 2007; Pollatos & Schandry, 2004; Schandry & Montoya, 1996). Thus, we controlled for ECG-related effects by subtracting the *baseline condition* from the *heartbeat-interval conditions*. A similar procedure is typically used in studies on sensory suppression for self-generated sounds, in which a motor condition in which no sounds are presented is subtracted from the motor + auditory condition to control for motor-related EEG effects (Baess et al., 2009, 2011).

EEG was recorded at 2048 Hz using the Active-Two system (BioSemi, Amsterdam, Netherlands), consisting of 64 active electrodes that were placed in an EEG cap according to the standard 10/20 system. The horizontal and vertical EOG was measured by placing electrodes on the outer canthi and above and below the subject's left eye.

### 2.3. Data analysis

For the behavioral analysis we calculated the percentage of agreement (i.e. whether participants believed the sounds were related to their own heartbeats or not) for each of the experimental conditions, averaged across subjects. In addition, the average reaction times for the *active sound condition* were calculated.

For the EEG and ECG analysis, first an offline detection of the onset of the R-wave in the ECG signal was conducted, by using the algorithm implemented in Fieldtrip software (Oostenveld, Fries, Maris, & Schoffelen, 2011). More specifically, for detection of the R-wave the raw ECG data was de-trended and band-pass filtered between 4 and 80 Hz. Markers were placed for the onset of the R-wave and the average heart rate was calculated for each of the experimental conditions.

Next, for the *heartbeat-interval conditions* it was determined whether the sound that was presented online, was presented at the correct interval, by comparing the triggers that were placed online with the onsets of the R-wave that were detected offline. Trials in which the sound was presented at the correct interval were time-locked to the onset of the sound from -500 to 500 ms. A similar segmentation was used for the *external-sound condition*. Finally, for the *baseline condition* 6 different segmentations were conducted (i.e. from -500 to 500 ms, from -400 to 600 ms, from -300 to 700 ms, from -200 to 800 ms, from -100 to 900 ms and from 0 to 1000 ms with respect to the onset of the R-wave). In this way, each of the *heartbeat-interval conditions* could be compared with a corresponding baseline EEG epoch that was similarly synchronized to the ECG signal, but in which no sounds were presented.

For the EEG and ECG analysis, the EEG and ECG data were re-referenced to the linked mastoids and were band-pass filtered from 1 to 40 Hz (for a similar procedure, see: Gray et al., 2007). Trials in which the EEG signal was contaminated by ocular, movement-related or clipping artifacts were discarded from analysis by using an automated procedure implemented in the Fieldtrip software package (Oostenveld et al., 2011). No separate artifact rejection was conducted for the ECG signal, as based on the segmentation procedure described above we already selected only those trials in which a clear peak of the R-wave could be selected in the correct time-window. To calculate the auditory evoked potential (AEP), a pre-stimulus baseline correction was applied to both the EEG and the ECG signal from -100 to 0 ms with respect to the onset of the sound, as is common practice in research on sensory suppression (Baess et al., 2009).

To statistically evaluate the difference between conditions the N1 amplitude averaged over the interval from 140 to 170 ms for a  $3 \times 3$  spatial grid of fronto-central electrodes was selected. The following electrodes were included in the analysis: F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2, CP1, CPz and CP2 (the electrodes are highlighted in the ERP figures). The electrodes were selected a priori as previous studies have indicated that the auditory N1 component is maximal over these sites (Baess et al., 2011; Bendixen, SanMiguel, & Schroger, 2012). In a first analysis, all the different delay intervals were compared by using a repeated measures ANOVA with the factors Delay (0 ms, 100 ms, 200 ms, 300 ms, 400 ms, 500 ms), Front-to-Back (3 levels) and Left-to-Right (3 levels). Front-to-Back refers to the anterior-to-posterior spatial

<sup>1</sup> Exclusion of this participant did not alter the results for the behavioral data analysis (i.e. performance on the heartbeat detection task).



**Table 1**  
Behavioral data for the heart rate detection task.

	Response	
	Yes	No
0 ms interval	10 (71%)	4 (29%)
100 ms interval	12 (86%)	2 (14%)
200 ms interval	12 (86%)	2 (14%)
300 ms interval	10 (71%)	4 (29%)
400 ms interval	9 (64%)	5 (36%)
500 ms interval	8 (57%)	6 (44%)
External condition	9 (64%)	5 (36%)

Number and percentage (between brackets) of yes and no responses in the heart rate detection task for the different experimental conditions.

dimension of the electrode-grid and Left-to-Right refers to the spatial arrangement of the electrode grid from the left to the right hemisphere. Including these factors in the analysis allows making inferences about the spatial distribution of the effects observed. In a second analysis, we collapsed across the different heartbeat-interval conditions and compared the heartbeat-sound to the external sound condition by using a repeated measures ANOVA with the factors Condition (heartbeat-related vs. externally generated) Front-to-Back (3 levels) and Left-to-Right (3 levels). In the analysis of the EEG data we checked for the assumption of sphericity, by using Mauchly's test and the Greenhouse–Geisser correction was applied when appropriate.

A main problem for time-locking the data to the heartbeats is the possibility of systematic ECG-related artifacts affecting the EEG signal (Fortgens & Debruin, 1983; Nakamura & Shibasaki, 1987) and the possibility that the heartbeat-evoked potential (HEP) partly overlies our effects of interest (Schandry and Montoya, 1996; Yuan, Yan, Xu, Han, & Yan, 2007). To control for the potential confound that eventual differences between the heartbeat-interval sound and the external sound conditions were primarily related to ECG-related effects, in an additional analysis the corresponding baseline condition was subtracted for each of the heartbeat-interval conditions. Thus, we report both the ECG-uncorrected and the ECG-corrected data.

### 3. Results

#### 3.1. Behavioral results

##### 3.1.1. Heartbeat detection

Table 1 shows that the agreement on whether the sounds reflected the own heartbeat followed an inversed U-shape pattern. Most participants tended to agree that sounds in the 100 ms and the 200 ms delay condition reflected their own heartbeat, but for the other conditions the ratings were more variable. However, statistical analysis using a  $\chi^2$  test indicated that the distribution of yes and no responses was not different from what can be expected based on chance,  $\chi^2(6) = 4.9$ ,  $p = .56$ . Furthermore, a random permutation test showed that the observed percentage of correctly classified sounds did not lie outside the 95% distribution that would be expected when subjects would perform at chance level. This indicates that participants responded at chance level and were not able to detect whether the sounds presented corresponded to their own heartbeat or not.<sup>2</sup> The individual performance data on the heartbeat detection task is included as supplementary material online. In the active-sound condition, the average reaction time was 755 ms (SD = 93 ms). Analysis of the heart rate and the heart rate variability is included in the supplementary material online.

<sup>2</sup> A post hoc power analysis (using  $\lambda = .041$ ) indicates a power of .56 ( $\beta = .44$ ). Given the fact that the  $\chi^2$  test may give inaccurate results with low numbers of subjects, the absence of a behavioral difference may be related to the relatively low number of subjects that was used in the present study.

**Table 2**  
Descriptives of EEG data analysis.

Interval	% of Trials missing	% of Trials rejected	Avg. # of trials
0 ms	8.0	42.4	142
100 ms	10.8	49.1	121
200 ms	8.6	44.9	135
300 ms	10.5	51.9	113
400 ms	6.8	43.1	141
500 ms	8.2	42.8	139
External	n.a.	44.9	156
Active	n.a.	57.7	99

The different experimental conditions are represented at different lines. The % of trials missing refers to the percentage of trials that was rejected because the online detection algorithm did not present the sound at the interval specified. The % of trials rejected refers to the percentage of trials that was rejected because of ocular, movement- or clipping-related artifacts. The avg. # of trials represents the average number of trials that was included per participant in the calculation of the ERPs.

#### 3.2. Event-related potentials

##### 3.2.1. Different heartbeat-interval conditions (uncorrected for ECG-related artifacts)

Table 2 represents the percentage of trials that was rejected because the sound was not presented in the interval specified, the percentage of trials that was rejected based on artifacts and the average number of trials per participant that was included in the final ERP analysis.

Fig. 1 represents the event-related potentials (ERPs) and the averaged ECG for the different heartbeat-interval conditions.<sup>3</sup> All auditory ERPs were time-locked to the onset of the sound and as can be seen in the upper and lower panel of Fig. 1, the auditory N1 peaked around 150 ms after stimulus onset.

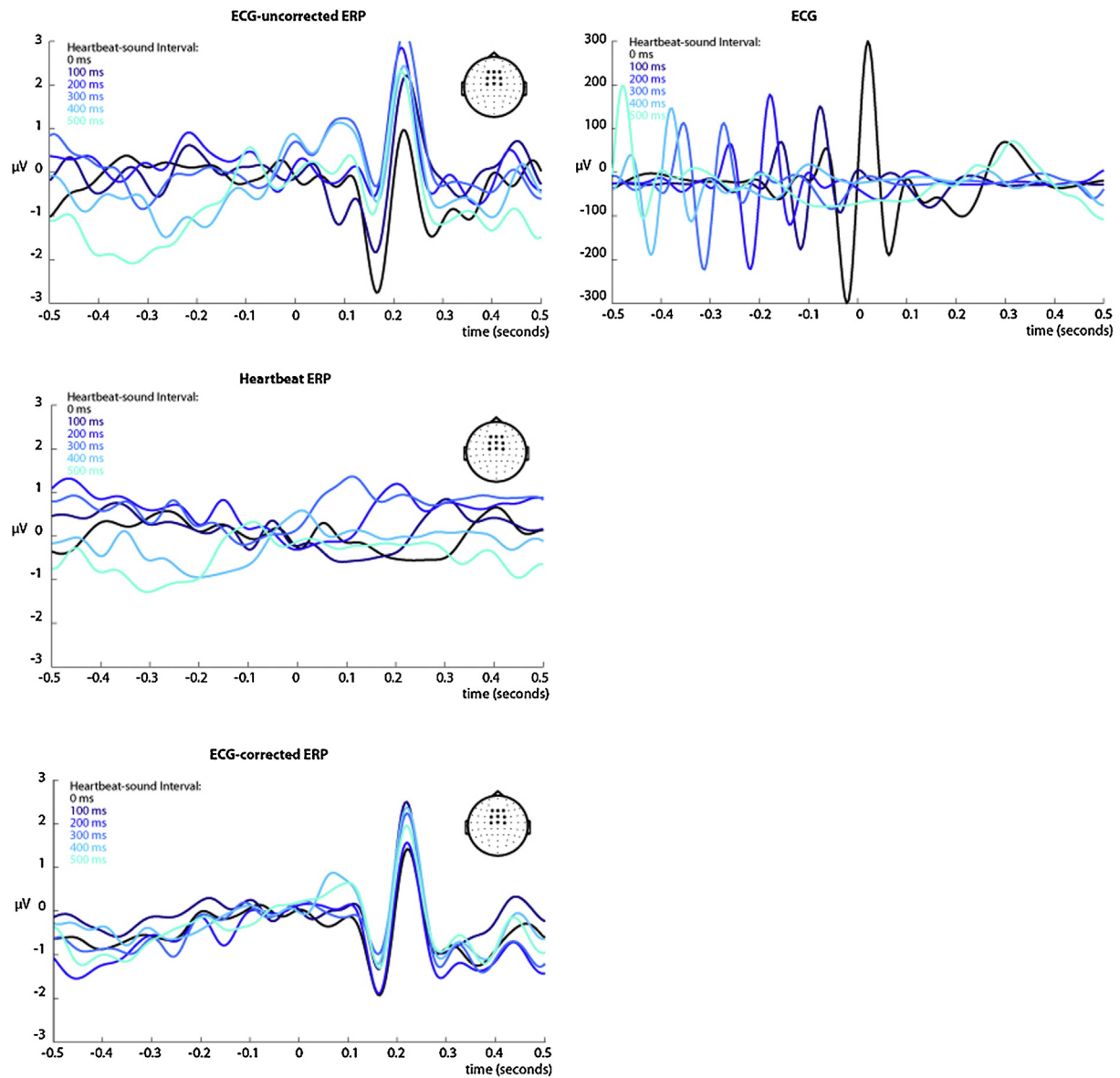
The analysis of the ECG-uncorrected ERPs (left upper panel of Fig. 1) showed a main effect of Delay,  $F(5,65) = 8.0$ ,  $p < .001$ ,  $\eta^2 = .38$  and an interaction between Delay and Front-to-Back,  $F(10,130) = 4.1$ ,  $p < .01$ ,  $\eta^2 = .24$ . The interaction effect reflected that the differences between conditions were most pronounced at frontal compared to more posterior electrodes (see Fig. 2). Post hoc *t*-tests indicated significant differences in the N1 amplitude between the following conditions: '0 ms vs. 200 ms', '0 ms vs. 300 ms', '0 ms vs. 400 ms', '0 ms vs. 500 ms', '100 ms vs. 200 ms', '100 ms vs. 300 ms', '100 ms vs. 400 ms', '100 ms vs. 500 ms', '200 ms vs. 300 ms', '300 ms vs. 400 ms' (all  $ps < .05$ ; see Fig. 1).

##### 3.2.2. Different heartbeat-interval conditions (corrected for ECG-related artifacts)

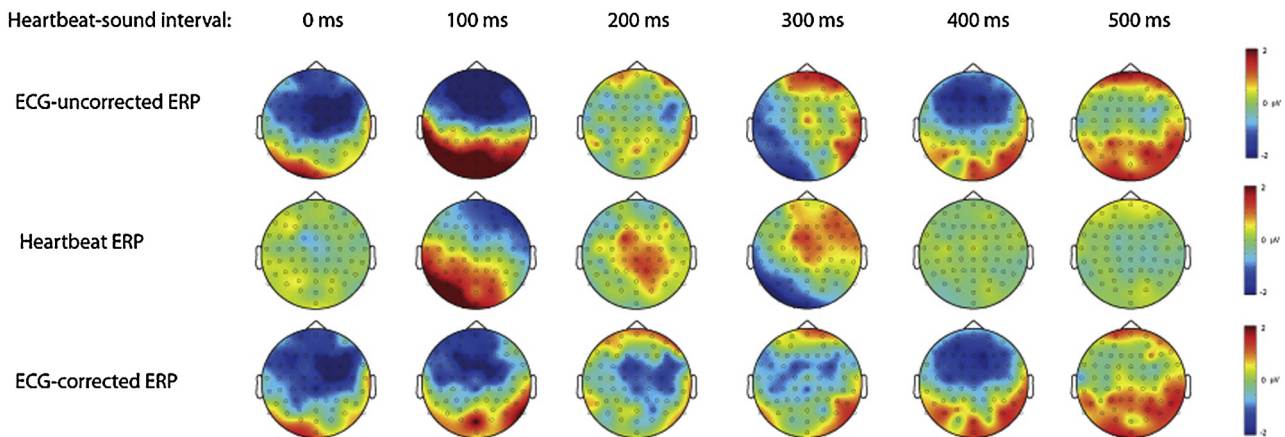
As can be seen in the ERPs in the middle panel of Fig. 1 and in the topoplots in the middle panel of Fig. 2, each of the heartbeat-interval conditions were differentially affected by ECG-related effects. To investigate to what extent the different ERP responses were related to heartbeat-related effects, we subtracted the baseline condition in which no sound was presented (see middle plots in Figs. 1 and 2) from the different heartbeat-interval conditions. A similar procedure is typically applied in studies on sensory attenuation, in which a pure motor condition is subtracted from the auditory + motor condition (Baess et al., 2009, 2011). In this way we obtained ERPs that should selectively reflect the auditory component, irrespective of the ECG-related effects (see lower panel in Figs. 1 and 2).

After correction for ECG-related effects, the main effect of Delay was no longer significant,  $F(5,65) = 1.2$ ,  $p = .35$ ,  $\eta^2 = .08$ . The absence of a main effect of Delay indicates that the effects observed in the

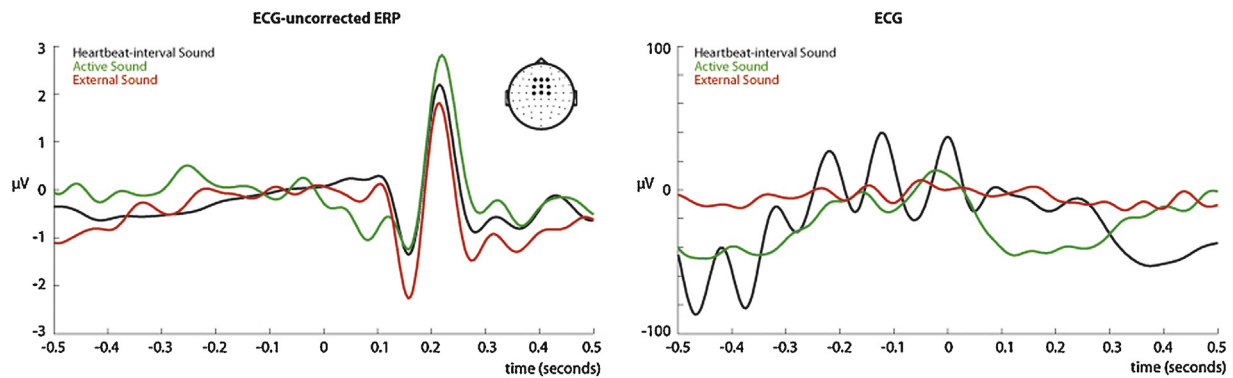
<sup>3</sup> The ECG represents the averaged signal across both ECG electrodes that was subsequently baseline-corrected for the EEG/ECG analysis.



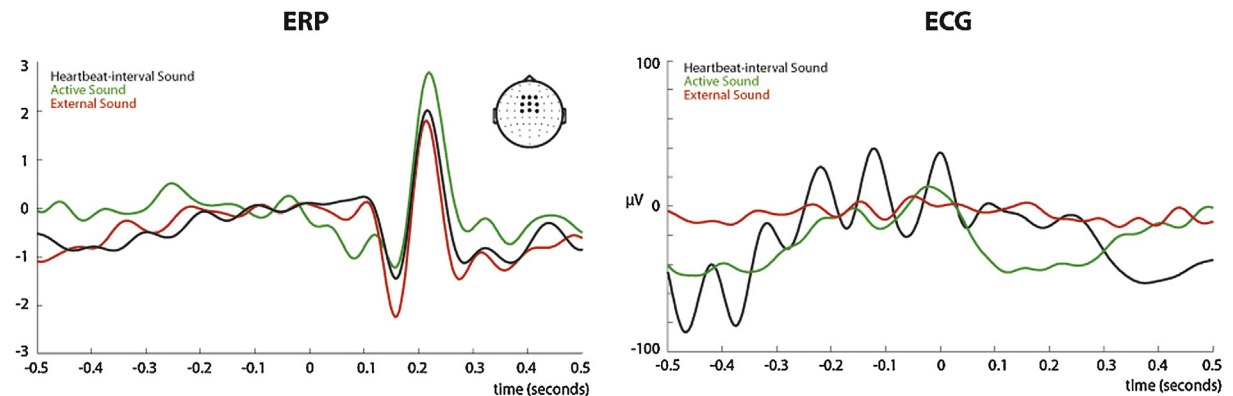
**Fig. 1.** Event-related potentials and ECG. Each graph represents the ERPs for the different heartbeat-interval conditions (0, 100, 200, 300, 400 and 500 ms intervals). The upper graph represents the ECG-uncorrected ERPs (Auditory + Heartbeat ERP), the middle graph represents the baseline condition in which no sounds were presented (Heartbeat ERP) and the lower graph represents the ECG-corrected ERPs (i.e. difference between the heartbeat-interval and the baseline conditions).



**Fig. 2.** Topoplots representing the auditory N1-interval (140–170 ms). Topoplots in different columns represent the different heartbeat-interval conditions (i.e. 0, 100, 200, 300, 400 and 500 ms intervals). The upper row represents the ECG-uncorrected ERPs (Auditory + Heartbeat ERP), the middle row represents the baseline condition in which no sounds were presented (Heartbeat ERP) and the lower row represents the ECG-corrected ERPs (i.e. difference between the heartbeat-interval and the baseline conditions).



**Fig. 3.** Event-related potentials and ECG for the collapsed heartbeat-interval conditions uncorrected for ECG-related artifacts. Each graph represents the ERPs time-locked to the auditory stimulus in the heartbeat-interval conditions (black lines), the active-sound conditions (green lines) and the external-sound conditions (red lines). (For interpretation of the references to color in this legend, the reader is referred to the web version of the article.)



**Fig. 4.** Event-related potentials and ECG for the collapsed heartbeat-interval conditions. Each graph represents the ERPs time-locked to the auditory stimulus in the heartbeat-interval conditions (black lines), the active-sound conditions (green lines) and the external-sound conditions (red lines). (For interpretation of the references to color in this legend, the reader is referred to the web version of the article.)

uncorrected ERPs were probably primarily related to ECG-related effects (i.e. ECG artifacts and/or the heartbeat evoked potential).

### 3.2.3. Event-related potentials for the collapsed heartbeat-interval conditions

Next, we collapsed the data across the different heartbeat-interval conditions. The rationale for collapsing across the different intervals was twofold. First, both the behavioral and the EEG analysis did not yield statistically significant differences between the different heartbeat-interval conditions. Still, it could well be that the heartbeat-interval conditions differ from externally generated sounds. By collapsing across the different intervals, we avoid the problem of multiple comparisons between the different heartbeat sound and the external sound condition. Furthermore, although we corrected for ECG-related artifacts by subtracting the baseline from the experimental conditions, there is still a possibility of residual ECG-related artifacts. By collapsing across the different delays we avoided this possible confound, by ‘spreading out’ the ECG-related effects over a 500 ms range.

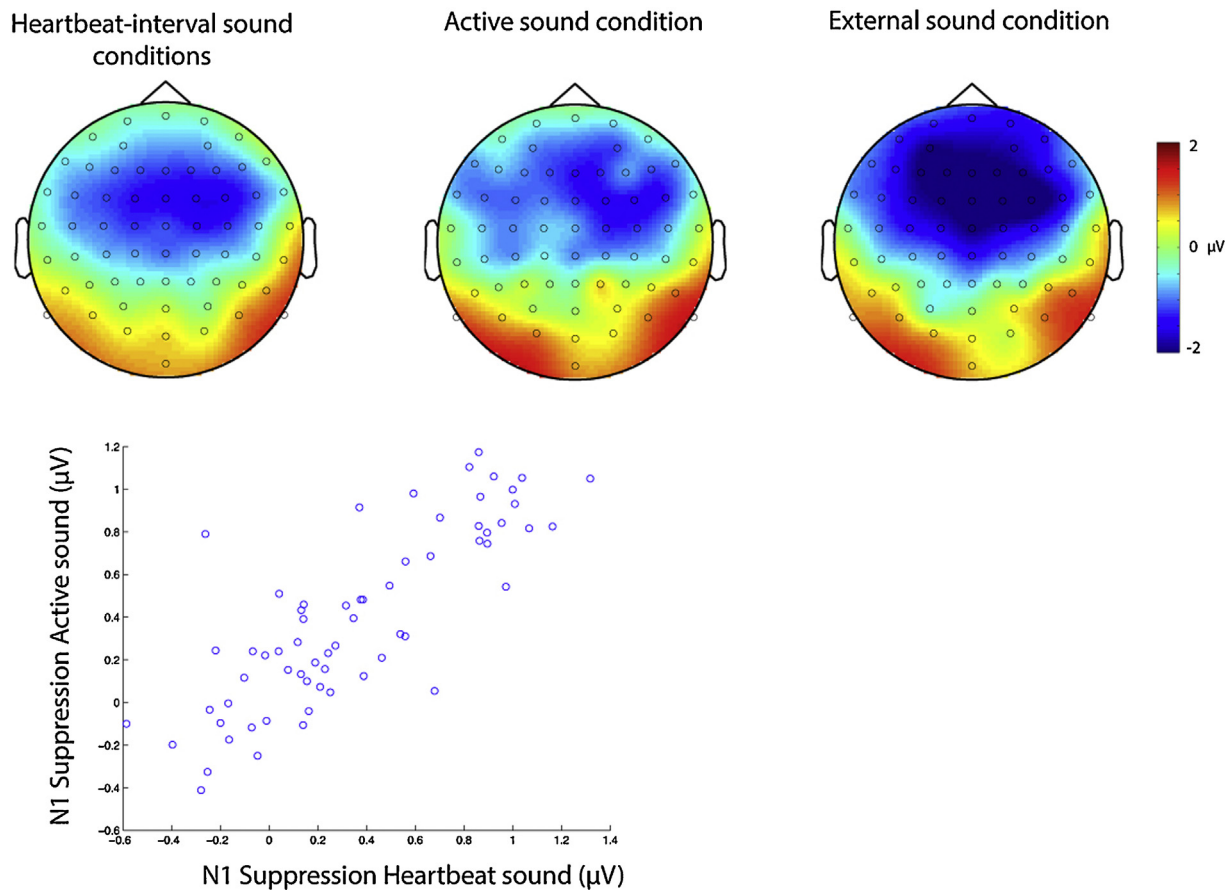
The ERPs for the collapsed heartbeat-interval conditions and the external and active conditions are represented in Fig. 3. Analysis of the ERPs collapsed across the different heartbeat-interval conditions but uncorrected for ECG-related effects (see Fig. 3) showed a significant difference between the heartbeat-interval conditions and the external sound conditions,  $F(1, 13) = 5.5$ ,  $p < .05$ ,  $\eta^2 = .30$ . An interaction was observed between Condition, Front-to-Back and Left-to-Right,  $F(4, 52) = 3.9$ ,  $p < .05$ ,  $\eta^2 = .23$ , reflecting that the difference was most pronounced at right frontal sites.

The ERPs for the collapsed heartbeat-interval conditions – corrected for ECG-related artifacts – and the external and active conditions are represented in Fig. 4. Analysis of the ERPs showed a marginally significant difference between the heartbeat-interval conditions and the external sound conditions,  $F(1, 13) = 3.9$ ,  $p = .07$ ,  $\eta^2 = .23$  reflected in a smaller auditory N1 amplitude for heartbeat-related compared to externally generated sounds. The difference between the active-sound condition and the external-sound condition was not significant,  $F(1, 13) = 2.5$ ,  $p = .14$ ,  $\eta^2 = .19$ .<sup>4</sup>

We directly compared the topographical distribution of the N1-suppression for heartbeat-related and actively generated sounds. To this aim the correlation between both conditions was calculated across all electrodes (for a similar analysis, see: e.g. van Elk, van Schie, Zwaan, & Bekkering, 2010). A strong and highly significant correlation was observed,  $r = .87$ ,  $p < .001$ , indicating a comparable topographical distribution of the N1-suppression effect for both conditions (see Fig. 5).

In an additional analysis, we controlled for the differential number of trials per condition. That is, because the *heartbeat-interval conditions* were presented 6 times, the collapsed *heartbeat-interval ERP* was comprised of about 6 times more trials than the *external condition*. For each subject we randomly selected the same number of trials from the *heartbeat-interval conditions* as the *external condition* and by averaging we obtained ERPs that were matched for the

<sup>4</sup> This is probably related to the fact that no baseline motor condition was included in the present experiment to correct for motor-related effects overlying the auditory N1-suppression (Baess et al., 2008, 2011).



**Fig. 5.** Topoplots of the auditory N1-interval (140–170 ms) for the collapsed heartbeat-interval conditions. Topoplots for the heartbeat-interval conditions (left plots), the active-sound condition (middle plot) and the external-sound condition (right plot). The lower plot represents the correlation between the topographic distribution of the N1 suppression for heartbeat sounds (x-axis) and active sounds (y-axis).

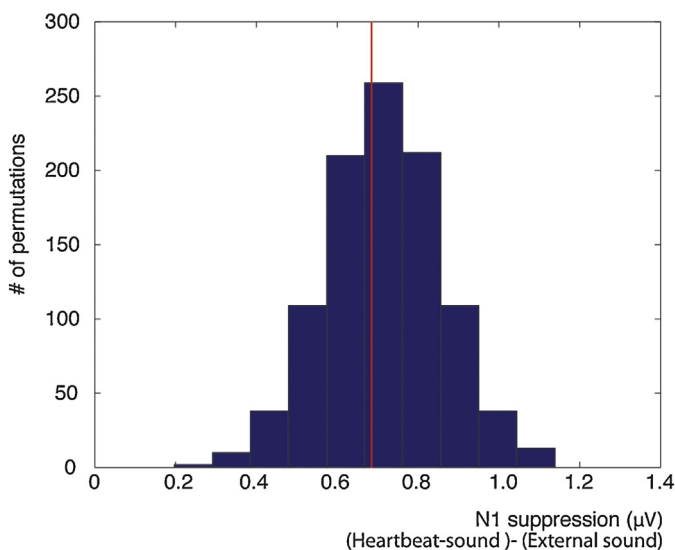
number of trials for the different conditions. Next, we calculated the N1-suppression by subtracting the N1 for the heartbeat-interval condition from the external-sound condition. As can be seen in the histogram in Fig. 6, in all random trial selections the heartbeat

sound condition resulted in an N1-suppression compared to the external-sound condition (i.e. all values are positive). In addition, it can be seen that the observed N1-suppression for the different trial selections are normally distributed around the actual N1-suppression (i.e. red line in histogram). This finding indicates that the N1 difference between the heartbeat-interval and the external sound condition was robust and could be observed irrespective of the number of trials that comprised the individual ERPs.

During the heartbeat-interval conditions, sounds were presented at every heartbeat. Thus on average, during the heartbeat sound condition the rate of stimulus presentation was 66.6 auditory stimuli per minute. During the external sound condition auditory stimuli were presented every  $900 \pm 200$  ms, thus resulting in a stimulus presentation rate of 66.7 auditory stimuli per minute. Statistical analysis confirmed that for none of the heartbeat-interval conditions the stimulus presentation rate differed significantly from the external-sound condition. Thus, frequency of presentation cannot underlie the suppression that was observed for the heartbeat-interval conditions.

#### 3.2.4. Individual differences in heartbeat detection and N1 suppression

We were interested in how individual differences in heartbeat detection ability were related to the strength of the N1 suppression in relation to heartbeat related sounds. However, analysis of the behavioral data indicates that most subjects performed at chance level in the heartbeat detection task. In a correlation analysis, no significant correlations were observed between the heartbeat detection data and the sensory suppression reflected in the N1



**Fig. 6.** The histogram represents the observed N1-suppression (i.e. difference between the N1 for the Heartbeat-interval and the external-sound conditions), after 1000 random trial-selections. The red line represents the actual N1-suppression that was reported in the main analysis.



component (see Supplementary Material Online). These findings indicate that the sensory suppression for heartbeat-related sounds was not related to individual differences in heartbeat detection ability.

#### 4. Discussion

In the present EEG study we observed sensory suppression, reflected in a reduced auditory N1 component for sounds that were related to one's heartbeat compared to externally generated sounds. Suppression of the auditory N1 is a robust finding in studies on agency comparing self-generated to externally generated sounds (Baess et al., 2011; Bass et al., 2008; Chen et al., 2012; Gentsch et al., 2012; Gentsch & Schutz-Bosbach, 2011; Horvath et al., 2012; Martikainen et al., 2005; Sowman et al., 2012; Stekelenburg & Vroomen, 2012). Typically, in these studies participants are required to press a button, which results in the presentation of an auditory stimulus at a predictable interval. The reduced auditory N1 for actively generated sounds has been proposed to reflect a mechanism of predictive coding in which the brain uses efference copy signals from motor and premotor regions in sensory and other cortical regions. It has been suggested that the auditory N1 component originates from the primary auditory cortex/Heschl's gyrus (Godey et al., 2001; Huotilainen et al., 1998; Mulert et al., 2005) and that the suppression of the N1-amplitude for self-generated sounds may reflect a top-down modulation of the auditory cortex (Aliu et al., 2009; Baess et al., 2009). The attenuation of the auditory cortex in response to actively generated sounds (and of the somatosensory cortex in response to touches) likely underlies our feeling of agency and helps us to distinguish self-generated from other-generated action effects (Blakemore et al., 1998, 2000).

##### 4.1. N1 suppression for heartbeat-related sounds

Our data show that the N1-suppression for heartbeat sounds was comparable in both amplitude and scalp distribution to the N1-suppression for sounds generated by our subjects when pressing a button. Accordingly it could be hypothesized that the auditory suppression that we observed for heartbeat-related sounds reflects a similar top-down modulation of the auditory cortex, based on visceral signals originating from the posterior insular cortex (Craig, 2002, 2003). Recently, such signals have been described in the insula in rodents and non-human monkeys (Jezzini, Caruana, Stoianov, Gallese, & Rizzolatti, 2012). Clinical studies have also suggested the presence of cortical visceral processing in the insula and the temporal cortex (Acosta & Pegalajar, 2003; Oppenheimer, Gelb, Girvin, & Hachinski, 1992; Oppenheimer, 1993; Seeck, Blanke, & Zaim, 2002; Seeck et al., 2003). Thus, focal epilepsy may cause asystolia and other cardiac abnormalities (Marynissen, Govers, & Vydt, 2012) and electrical stimulation of the insula may lead to brady- and tachycardia (Oppenheimer et al., 1992). Mechanoreceptors in the chest or within the heart itself may transduce the signals produced by the ventricular contraction (Knapp & Brener, 1998; Pauli, Hartl, Marquardt, Stalman, & Strian, 1991) which are further transmitted to the brainstem via the vagus nervus (Cameron, 2009). From there visceral signals related to the heart project to the insula (Augustine, 1996; Mesulam & Mufson, 1982; Zhang, Dougherty, & Oppenheimer, 1999) and the anterior cingulate cortex (Craig, 2002, 2009; Ongur & Price, 2000). The current finding of auditory suppression for heartbeat related sounds may indicate that the brain uses these visceral signals to distinguish heartbeat-related from externally generated sounds.

An important question is what the functional significance could be of auditory suppression for heartbeat-related sounds. Predicting the sensory consequences of one's actions is crucial for generating

a feeling of agency. Furthermore, many studies have shown that bodily self-consciousness relies on the integration of multisensory information and that for instance congruent visuotactile stimulation results in modulations of body ownership (e.g. Blanke, 2012; Blanke & Metzinger, 2009; Ehrsson, Spence, & Passingham, 2004; Ionta, Gassert, & Blanke, 2011; Lenggenhager, Mouthon, & Blanke, 2009; Lenggenhager et al., 2007; Tsakiris, Hesse, Boy, Haggard, & Fink, 2007). Similarly, it could be that predicting the sensory consequences of one's visceral signals supports a process of bodily self-consciousness (Seth, Suzuki, & Critchley, 2012). That is, the automatic integration of visceral signals and peripheral sensory signals may support the feeling that these sensory signals are actually related to one's body (Damasio, 2000). In support of this account, in a recent study it was found that cardiac signals could influence bodily self-consciousness as measured at an implicit level with the full body illusion, even though participants were not aware that they were observing heartbeat-related signals (Aspell et al., 2013). Other studies have also indicated that the multisensory integration of cardiac and exteroceptive signals supports a feeling of body ownership (Suzuki et al., 2013; Tsakiris, Tajadura-Jimenez, & Costantini, 2011). Finally, it has been argued that the disintegration of exteroceptive bodily signals and interoceptive signals in the posterior insula results in complex disorders of body ownership, such as heautoscopy (Heydrich & Blanke, 2013b).

The automatic integration of interoceptive and external sensory signals may also provide a predictive mechanism to distinguish internally generated sensations from externally generated sensations. As some bodily sensations can be perceived exteroceptively (e.g. one can 'hear' one's heartbeat when lying in bed, or one can perceive the sensory consequences of breathing) such a predictive mechanism would reduce the attentional load and general processing load associated with processing peripheral sensory signals. This idea is closely related to the interoceptive predictive coding model (Paulus & Stein, 2006; Seth et al., 2012), according to which predicted signals regarding one's body are compared with afferent visceral signals. Drawing a parallel with the predictive coding model of agency (Bubic, von Cramon, & Schubotz, 2010; Friston & Kiebel, 2009; Frith, 2005), it is proposed that a mismatch between expected and observed interoceptive signals results in an interoceptive prediction error, which may be associated with increased feelings of anxiety and depersonalization or derealization (Paulus & Stein, 2006; Seth et al., 2012). The finding of N1-suppression for heartbeat-related sounds may provide preliminary evidence for such proposed interoceptive coding, indicating that the brain can use visceral information to determine whether external sensory signals are related to interoceptive signals.

##### 4.2. Relation with ECG and heartbeat-evoked potential (HEP)

Contrary to our initial expectations, we did not observe a differential sensory suppression for sounds presented at different intervals with respect to the heartbeat. N1 suppression was observed for sounds when stimuli were collapsed across all delay conditions (0–500 ms). This approach seems warranted because of the absence of behavioral differences in heartbeat detection accuracy for the different intervals. In addition, by collapsing across different heartbeat-interval intervals we reduced the potential confound that ECG-related artifacts or the heartbeat-evoked potential could actually underlie differences between the present experimental conditions. Finally, due to inter-individual variation in the temporal location of subjects' heartbeat perceptions, likely related to biological differences, participants may actually perceive different intervals to be in synchrony with their heartbeat (Brener, Knapp, & Ring, 1995; Wiens & Palmer, 2001). The finding that sensory suppression was not modulated according to the delay between



the sound and the heart beat, is in line with findings from a recent study on sensory suppression in response to self-generated sounds, in which we also confirmed that sensory suppression occurs irrespective of the temporal delay between one's button press and a subsequently presented sound (van Elk et al., *resubmitted*).

It is important to note that the difference between the heartbeat-related sound conditions and the externally generated sound conditions cannot be accounted for by a differential number of total sound stimuli or a differential auditory stimulus presentation rate. The difference that we observed persisted after both conditions were matched for the number of trials. Further analysis revealed that the stimulus presentation rate was similar for both conditions. Thus, the sensory suppression that we observed for heartbeat-related compared to externally generated sounds was robust and persisted after controlling for ECG-related artifacts, the number of trials involved and the phase of the cardiac cycle.

The effects that we observed for heartbeat-related sounds were clearly different from the heartbeat-evoked potential (HEP) that has been described in other studies (Gray et al., 2007; Leopold & Schandry, 2001; Pollatos, Kirsch, & Schandry, 2005; Pollatos & Schandry, 2004; Schandry & Montoya, 1996; Shao, Shen, Wilder-Smith, & Li, 2011). The HEP is obtained by time-locking the EEG signal to the onset of the R-wave and supposedly reflects a cortical marker associated with the processing of afferent visceral signals related to the heart (Fukushima et al., 2011; Gray et al., 2007; Pollatos et al., 2005; Pollatos & Schandry, 2004; Schandry & Montoya, 1996). It has been found for instance that the heartbeat-evoked potential (HEP) has a larger amplitude in good perceivers compared to bad perceivers (Pollatos et al., 2005; Pollatos & Schandry, 2004). In our baseline condition no sounds were presented and besides the ECG-related artifacts that were clearly lateralized to the left hemisphere, we also observed an HEP-like response, with a similar scalp distribution and polarity as observed in previous studies (see middle panel of Fig. 2). By subtracting the baseline condition from the auditory heartbeat conditions, we corrected for the possibility that our effects were partly confounded with ECG-related effects. A similar approach has been used in studies on actively generated sounds, in which motor-responses are subtracted from auditory + motor responses to obtain an unbiased estimate of sensory suppression (Baess et al., 2009, 2011). In addition, by collapsing across different heartbeat-intervals we avoided the possibility that the auditory N1 response was systematically contaminated by artifacts of the same phase of the cardiac cycle.

#### 4.3. Shortcomings and limitations

In the present experiment participants were unable to detect whether sounds corresponded to their heartbeat or not. The absence of behavioral effects in the present study could be related to the prolonged interval that was used in for presenting heartbeat-related sounds (4min), which was a necessary consequence of the experimental setup and procedure. Previous studies using the Method of Constant Stimuli have used shorter intervals, allowing repeated measures per subject to obtain a more reliable estimate of one's heart rate detection ability (Brenner et al., 1993; Brenner, Ring, & Liu, 1994; Schneider et al., 1998). In addition, feedback about the accuracy of one's heartbeat perception typically improves performance on this task (e.g. Carroll, 1977), whereas in the present study participants did not receive feedback about their accuracy.

In addition to these concerns related to the specific paradigm that was used, the absence of behavioral effects could also be related to the relatively low number of participants that was tested, resulting in low statistical power. Furthermore, we did not control for other confounding factors that may affect interoceptive accuracy, such as the body mass index, sex differences, time estimation

ability and the specific instruction that was given to participants (i.e. Ehlers, Breuer, Dohn, & Fiegenbaum, 1995). Accordingly, the precise relation between heartbeat detection accuracy and interoceptive predictive coding as measured with the EEG remains to be determined in future studies. Still, the finding that we observed sensory suppression for heart beat-related sounds even with a relatively small number of participants, suggests that this may reflect a strong and automatic effect related to the processing of heart beat related signals.

## 5. Conclusions

In sum, the present study suggests that the auditory cortex automatically differentiates between heartbeat-related and externally generated sounds through a process of sensory suppression, based on visceral signals. This finding indicates that a comparable functional mechanism of predictive coding may underlie the processing of heartbeat- and action-related information. We speculate that the automatic suppression of heartbeat-related sounds may support bodily self-consciousness (Aspell et al., 2013), likely through a process of interoceptive predictive coding (Paulus & Stein, 2006; Seth et al., 2012).

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.biopsycho.2014.03.004>.

## References

- Acosta, A., & Pegalajar, J. (2003). Facilitation of heartbeat self-detection in a choice task. *International Journal of Psychophysiology*, 47(2), 139–146.
- Aliu, S. O., Houde, J. F., & Nagarajan, S. S. (2009). Motor-induced suppression of the auditory cortex. *Journal of Cognitive Neuroscience*, 21(4), 791–802.
- Aspell, J. E., Heydrich, L., Marillier, G., Lavanchy, T., Herbelin, B., & Blanke, O. (2013). Turning body and self inside out: Visualized heartbeats alter bodily self-consciousness and tactile perception. *Psychological Science*, 24(12), 2445–2453.
- Aspell, J. E., Lavanchy, T., Lenggenhager, B., & Blanke, O. (2010). Seeing the body modulates audiotactile integration. *European Journal of Neuroscience*, 31(10), 1868–1873.
- Augustine, J. R. (1996). Circuitry and functional aspects of the insular lobe in primates including humans. *Brain Research Reviews*, 22(3), 229–244.
- Baess, P., Horvath, J., Jacobsen, T., & Schroger, E. (2011). Selective suppression of self-initiated sounds in an auditory stream: An ERP study. *Psychophysiology*, 48(9), 1276–1283.
- Baess, P., Widmann, A., Roye, A., Schroger, E., & Jacobsen, T. (2009). Attenuated human auditory middle latency response and evoked 40-Hz response to self-initiated sounds. *European Journal of Neuroscience*, 29(7), 1514–1521.
- Bass, P., Jacobsen, T., & Schroger, E. (2008). Suppression of the auditory N1 event-related potential component with unpredictable self-initiated tones: Evidence for internal forward models with dynamic stimulation. *International Journal of Psychophysiology*, 70(2), 137–143.
- Bendixen, A., SanMiguel, I., & Schroger, E. (2012). Early electrophysiological indicators for predictive processing in audition: A review. *International Journal of Psychophysiology*, 83(2), 120–131.
- Blakemore, S. J., Wolpert, D., & Frith, C. D. (2000). Why can't you tickle yourself? *Neuroreport*, 11(11), R11–R16.
- Blakemore, S. J., Wolpert, D. M., & Frith, C. D. (1998). Central cancellation of self-produced tickle sensation. *Nature Neuroscience*, 1(7), 635–640.
- Blanke, O. (2012). Multisensory brain mechanisms of bodily self-consciousness. *Nature Reviews. Neuroscience*, 13(8), 556–571.

- Blanke, O., Landis, T., Spinelli, L., & Seeck, M. (2004). Out-of-body experience and autoscoping of neurological origin. *Brain*, 127, 243–258.
- Blanke, O., & Metzinger, T. (2009). Full-body illusions and minimal phenomenal selfhood. *Trends in Cognitive Sciences*, 13(1), 7–13.
- Brener, J., & Kluitse, C. (1988). Heartbeat detection: Judgments of the simultaneity of external stimuli and heartbeats. *Psychophysiology*, 25(5), 554–561.
- Brener, J., Knapp, K., & Ring, C. (1995). The effects of manipulating beliefs about heart rate on the accuracy of heartbeat counting in the Schandry task. *Psychophysiology*, 32(S22).
- Brener, J., Liu, X., & Ring, C. (1993). A method of constant stimuli for examining heartbeat detection: Comparison with the Brener–Kluitse and Whitehead methods. *Psychophysiology*, 30(6), 657–665.
- Brener, J., Ring, C., & Liu, X. (1994). Effects of data limitations on heartbeat detection in the method of constant stimuli. *Psychophysiology*, 31(3), 309–312.
- Bubic, A., von Cramon, D. Y., & Schubotz, R. I. (2010). Prediction, cognition and the brain. *Frontiers in Human Neuroscience*, 4, 25.
- Cameron, O. G. (2009). Visceral brain–body information transfer. *Neuroimage*, 47(3), 787–794.
- Carroll, D. (1977). Cardiac perception and cardiac control. A review. *Biofeedback and Self-Regulation*, 2(4), 349–369.
- Chen, Z., Liu, P., Wang, E. Q., Larson, C. R., Huang, D., & Liu, H. (2012). ERP correlates of language-specific processing of auditory pitch feedback during self-vocalization. *Brain and Language*, 121(1), 25–34.
- Craig, A. D. (2002). How do you feel? Interoception: The sense of the physiological condition of the body. *Nature Reviews. Neuroscience*, 3(8), 655–666.
- Craig, A. D. (2003). Interoception: The sense of the physiological condition of the body. *Current Opinion in Neurobiology*, 13(4), 500–505.
- Craig, A. D. (2009). How do you feel now? The anterior insula and human awareness. *Nature Reviews. Neuroscience*, 10(1), 59–70.
- Critchley, H. D., Wiens, S., Rotstein, P., Ohman, A., & Dolan, R. J. (2004). Neural systems supporting interoceptive awareness. *Nature Neuroscience*, 7(2), 189–195.
- Dale, A., & Anderson, D. (1978). Information variables in voluntary control and classical conditioning of heart rate: Field dependence and heart-rate perception. *Perceptual & Motor Skills*, 47(1), 79–85.
- Damasio, A. (2000). *The feeling of what happens: Body and emotion in the making of consciousness*. New York: Harcourt Brace.
- Davis, M. R., Langer, A. W., Sutterer, J. R., Gelling, P. D., & Marlin, M. (1986). Relative discriminability of heartbeat-contingent stimuli under three procedures for assessing cardiac perception. *Psychophysiology*, 23(1), 76–81.
- Ehlers, A., & Breuer, P. (1992). Increased cardiac awareness in panic disorder. *Journal of Abnormal Psychology*, 101(3), 371–382.
- Ehlers, A., & Breuer, P. (1996). How good are patients with panic disorder at perceiving their heartbeats? *Biological Psychology*, 42(1–2), 165–182.
- Ehlers, A., Breuer, P., Dohn, D., & Fiegenbaum, W. (1995). Heartbeat perception and panic disorder – Possible explanations for discrepant findings. *Behaviour Research and Therapy*, 33(1), 69–76.
- Ehrsson, H. H., Holmes, N. P., & Passingham, R. E. (2005). Touching a rubber hand: Feeling of body ownership is associated with activity in multisensory brain areas. *Journal of Neuroscience*, 25(45), 10564–10573.
- Ehrsson, H. H., Spence, C., & Passingham, R. E. (2004). That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb. *Science*, 305(5685), 875–877.
- Ferguson, M. L., & Katkin, E. S. (1996). Visceral perception, anhedonia, and emotion. *Biological Psychology*, 42(1–2), 131–145.
- Fortgens, C., & Debruin, M. P. (1983). Removal of eye-movement and ECG artifacts from non-cephalic reference EEG. *Electroencephalography and Clinical Neurophysiology*, 56(1), 90–96.
- Fourneret, P., & Jeannerod, M. (1998). Limited conscious monitoring of motor performance in normal subjects. *Neuropsychologia*, 36(11), 1133–1140.
- Franck, N., Farrer, C., Georgieff, N., Marie-Cardine, M., Dalery, J., d'Amato, T., et al. (2001). Defective recognition of one's own actions in patients with schizophrenia. *American Journal of Psychiatry*, 158(3), 454–459.
- Friston, K. (2012). Prediction, perception and agency. *International Journal of Psychophysiology*, 83(2), 248–252.
- Friston, K., & Kiebel, S. (2009). Predictive coding under the free-energy principle. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1521), 1211–1221.
- Frith, C. (2005). The neural basis of hallucinations and delusions. *Comptes Rendus Biologies*, 328(2), 169–175.
- Fukushima, H., Terasawa, Y., & Umeda, S. (2011). Association between interoception and empathy: Evidence from heartbeat-evoked brain potential. *International Journal of Psychophysiology*, 79(2), 259–265.
- Gallagher, I. I. (2000). Philosophical conceptions of the self: Implications for cognitive science. *Trends in Cognitive Sciences*, 4(1), 14–21.
- Gentsch, A., Kathmann, N., & Schutz-Bosbach, S. (2012). Reliability of sensory predictions determines the experience of self-agency. *Behavioural Brain Research*, 228(2), 415–422.
- Gentsch, A., & Schutz-Bosbach, S. (2011). I did it: Unconscious expectation of sensory consequences modulates the experience of self-agency and its functional signature. *Journal of Cognitive Neuroscience*, 23(12), 3817–3828.
- Godey, B., Schwartz, D., de Graaf, J. B., Chauvel, P., & Liegeois-Chauvel, C. (2001). Neuromagnetic source localization of auditory evoked fields and intracerebral evoked potentials: A comparison of data in the same patients. *Clinical Neurophysiology*, 112(10), 1850–1859.
- Gray, M. A., Taggart, P., Sutton, P. M., Groves, D., Holdright, D. R., Bradbury, D., et al. (2007). A cortical potential reflecting cardiac function. *Proceedings of the National Academy of Sciences of the USA*, 104(16), 6818–6823.
- Heydrich, L., & Blanke, O. (2013a). Distinct illusory own-body perceptions caused by damage to posterior insula and extrastriate cortex. *Brain*, 136, 790–803.
- Heydrich, L., & Blanke, O. (2013b). Distinct illusory own-body perceptions caused by damage to posterior insula and extrastriate cortex. *Brain*, 136(Pt 3), 790–803.
- Heydrich, L., Dieguez, S., Grunwald, T., Seeck, M., & Blanke, O. (2010). Illusory own body perceptions: Case reports and relevance for bodily self-consciousness. *Consciousness and Cognition*, 19(3), 702–710.
- Horvath, J., Maess, B., Baess, P., & Toth, A. (2012). Action-sound coincidences suppress evoked responses of the human auditory cortex in EEG and MEG. *Journal of Cognitive Neuroscience*, 24(9), 1919–1931.
- Hughes, G., Desantis, A., & Waszak, F. (2013). Mechanisms of intentional binding and sensory attenuation: The role of temporal prediction, temporal control, identity prediction, and motor prediction. *Psychological Bulletin*, 139(1), 133–151.
- Hughes, G., & Waszak, F. (2011). ERP correlates of action effect prediction and visual sensory attenuation in voluntary action. *Neuroimage*, 56(3), 1632–1640.
- Huotilainen, M., Winkler, I., Alho, K., Escera, C., Virtanen, J., Ilmoniemi, R. J., et al. (1998). Combined mapping of human auditory EEG and MEG responses. *Electroencephalography and Clinical Neurophysiology*, 108(4), 370–379.
- Ionta, S., Gasser, R., & Blanke, O. (2011). Multi-sensory and sensorimotor foundation of bodily self-consciousness – An interdisciplinary approach. *Frontiers in Psychology*, 2, 383.
- Jezzini, A., Caruana, F., Stoianov, I., Gallese, V., & Rizzolatti, G. (2012). Functional organization of the insula and inner perisylvian regions. *Proceedings of the National Academy of Sciences of the USA*, 109(25), 10077–10082.
- Jones, G. E. (1994). Perception of visceral sensations: A review of recent findings, methodologies, and future directions. In J. R. Jennings, P. K. Ackles, & M. G. H. Coles (Eds.), *Advances in psychophysiology* (vol. V. (Vols. 55–91)). London: Jessica Kingsley Publishers.
- Kannape, O. A., & Blanke, O. (2013). Self in motion: Sensorimotor and cognitive mechanisms in gait agency. *Journal of Neurophysiology*, 110(8), 1837–1847.
- Kannape, O. A., Schwabe, L., Tadi, T., & Blanke, O. (2010). The limits of agency in walking humans. *Neuropsychologia*, 48(6), 1628–1636.
- Katkin, E. S., Morell, M. A., Goldband, S., Bernstein, G. L., & Wise, J. A. (1982). Individual differences in heartbeat discrimination. *Psychophysiology*, 19(2), 160–166.
- Knapp, K. A., & Brener, J. (1998). Mechanoreceptors responsible for transducing heartbeat sensations. *Psychophysiology*, 35(S51).
- Lenggenhager, B., Mouthon, M., & Blanke, O. (2009). Spatial aspects of bodily self-consciousness. *Consciousness and Cognition*, 18(1), 110–117.
- Lenggenhager, B., Tadi, T., Metzinger, T., & Blanke, O. (2007). Video ergo sum: Manipulating bodily self-consciousness. *Science*, 317(5841), 1096–1099.
- Leopold, C., & Schandry, R. (2001). The heartbeat-evoked brain potential in patients suffering from diabetic neuropathy and in healthy control persons. *Clinical Neurophysiology*, 112(4), 674–682.
- Martikainen, M. H., Kaneko, K., & Hari, R. (2005). Suppressed responses to self-triggered sounds in the human auditory cortex. *Cereb Cortex*, 15(3), 299–302.
- Marynissen, T., Govers, N., & Vydts, T. (2012). Ictal asystole: Case report with review of literature. *Acta Cardiologica*, 67(4), 461–464.
- Mesulam, M. M., & Mufson, E. J. (1982). Insula of the old world monkey. III: Efferent cortical output and comments on function. *Journal of Comparative Neurology*, 212(1), 38–52.
- Mulert, C., Jager, L., Propp, S., Karch, S., Stormann, S., Pogarell, O., et al. (2005). Sound level dependence of the primary auditory cortex: Simultaneous measurement with 61-channel EEG and fMRI. *Neuroimage*, 28(1), 49–58.
- Nakamura, M., & Shibasaki, H. (1987). Elimination of EKG artifacts from EEG records: A new method of non-cephalic referential EEG recording. *Electroencephalography and Clinical Neurophysiology*, 66(1), 89–92.
- Ongur, D., & Price, J. L. (2000). The organization of networks within the orbital and medial prefrontal cortex of rats, monkeys and humans. *Cerebral Cortex*, 10(3), 206–219.
- Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, 156869.
- Oppenheimer, S. (1993). The anatomy and physiology of cortical mechanisms of cardiac control. *Stroke*, 24(12 Suppl), 13–15.
- Oppenheimer, S., Gelb, A., Girvin, J. P., & Hachinski, V. C. (1992). Cardiovascular effects of human insular cortex stimulation. *Neurology*, 42(9), 1727–1732.
- Pauli, P., Hartl, L., Marquardt, C., Stalman, H., & Strian, F. (1991). Heartbeat and arrhythmia perception in diabetic autonomic neuropathy. *Psychological Medicine*, 21, 413–421.
- Paulus, M. P., & Stein, M. B. (2006). An insular view of anxiety. *Biological Psychiatry*, 60(4), 383–387.
- Pollatos, O., Kirsch, W., & Schandry, R. (2005). Brain structures involved in interoceptive awareness and cardioafferent signal processing: A dipole source localization study. *Human Brain Mapping*, 26(1), 54–64.
- Pollatos, O., & Schandry, R. (2004). Accuracy of heartbeat perception is reflected in the amplitude of the heartbeat-evoked brain potential. *Psychophysiology*, 41(3), 476–482.
- Pollatos, O., Traut-Mattausch, E., & Schandry, R. (2009). Differential effects of anxiety and depression on interoceptive accuracy. *Depress Anxiety*, 26(2), 167–173.
- Ring, C., & Brener, J. (1992). The temporal locations of heartbeat sensations. *Psychophysiology*, 29(5), 535–545.
- Schandry, R. (1981). Heart beat perception and emotional experience. *Psychophysiology*, 18(4), 483–488.

- Schandry, R., & Montoya, P. (1996). Event-related brain potentials and the processing of cardiac activity. *Biological Psychology*, 42(1–2), 75–85.
- Schneider, T. R., Ring, C., & Katkin, E. S. (1998). A test of the validity of the method of constant stimuli as an index of heartbeat detection. *Psychophysiology*, 35(1), 86–89.
- Schulz, A., Lass-Hennemann, J., Sutterlin, S., Schachinger, H., & Voge, C. (2013). Cold pressor stress induces opposite effects on cardioceptive accuracy dependent on assessment paradigm. *Biological Psychology*, 93(1), 167–174.
- Seeck, M., Blanke, O., & Zaim, S. (2002). Temporal lobe epilepsy and postural orthostatic tachycardia syndrome (POTS). *Epilepsy and Behavior*, 3(3), 285–288.
- Seeck, M., Zaim, S., Chaves-Vischer, V., Blanke, O., Maeder-Ingvar, M., Weissert, M., et al. (2003). Ictal bradycardia in a young child with focal cortical dysplasia in the right insular cortex. *European Journal of Paediatric Neurology*, 7(4), 177–181.
- Seth, A. K., Suzuki, K., & Critchley, H. D. (2012). An interoceptive predictive coding model of conscious presence. *Frontiers in Psychology*, 2(395), 1–16.
- Shao, S., Shen, K., Wilder-Smith, E. P., & Li, X. (2011). Effect of pain perception on the heartbeat evoked potential. *Clinical Neurophysiology*, 122(9), 1838–1845.
- Sowman, P. F., Kuusik, A., & Johnson, B. W. (2012). Self-initiation and temporal cueing of monaural tones reduce the auditory N1 and P2. *Experimental Brain Research*, 222(1–2), 149–157.
- Stekelenburg, J. J., & Vroomen, J. (2012). Electrophysiological correlates of predictive coding of auditory location in the perception of natural audiovisual events. *Frontiers in Integrative Neuroscience*, 6, 26.
- Suzuki, K., Garfinkel, S. N., Critchley, H. D., & Seth, A. K. (2013). Multisensory integration across exteroceptive and interoceptive domains modulates self-experience in the rubber-hand illusion. *Neuropsychologia*, 51(13), 2909–2917.
- Tsakiris, M., Hesse, M. D., Boy, C., Haggard, P., & Fink, G. R. (2007). Neural signatures of body ownership: A sensory network for bodily self-consciousness. *Cerebral Cortex*, 17(10), 2235–2244.
- Tsakiris, M., Tajadura-Jimenez, A., & Costantini, M. (2011). Just a heartbeat away from one's body: Interoceptive sensitivity predicts malleability of body-representations. *Proceedings of the Royal Society B: Biological Sciences*, 278(1717), 2470–2476.
- van den Bos, E., & Jeannerod, M. (2002). Sense of body and sense of action both contribute to self-recognition. *Cognition*, 85(2), 177–187.
- Van der Does, W. A. J., Antony, M. M., Ehlers, A., & Barsky, A. J. (2000). Heartbeat perception in panic disorder: A reanalysis. *Behaviour Research and Therapy*, 38(1), 47–62.
- van Elk, M., Salomon, R., Kannape, O. A., & Blanke, O. (resubmitted). Suppression of the auditory evoked potential for actions generated by the upper and lower limbs.
- van Elk, M., van Schie, H. T., Zwaan, R. A., & Bekkering, H. (2010). The functional role of motor activation in language processing: Motor cortical oscillations support lexical-semantic retrieval. *Neuroimage*, 50(2), 665–677.
- von Holst, E., & Mittelstaedt, H. (1971). The principle of reafference: Interactions between the central nervous system and peripheral organs. In P. C. Dodwell (Ed.), *Perceptual processing: Stimulus equivalence and pattern recognition*. New York: Appleton.
- Weiskrantz, L., & Zhang, D. (1987). Residual tactile sensitivity with self-directed stimulation in hemianaesthesia. *Journal of Neurology, Neurosurgery & Psychiatry*, 50(5), 632–634.
- Whitehead, W. E., Drescher, V. M., Heiman, P., & Blackwell, B. (1977). Relation of heart rate control to heartbeat perception. *Biofeedback and Self-Regulation*, 2, 371–392.
- Wiens, S. (2005). Interoception in emotional experience. *Current Opinion in Neurology*, 18(4), 442–447.
- Wiens, S., Mezzacappa, E. S., & Katkin, E. S. (2000). Heartbeat detection and the experience of emotions. *Cognition & Emotion*, 14(3), 417–427.
- Wiens, S., & Palmer, S. N. (2001). Quadratic trend analysis and heartbeat detection. *Biological Psychology*, 58(2), 159–175.
- Wolpert, D. M. (1997). Computational approaches to motor control. *Trends in Cognitive Sciences*, 1(6), 209–216.
- Yates, A. J., Jones, K. E., Marie, G. V., & Hogben, J. H. (1985). Detection of the heartbeat and events in the cardiac cycle. *Psychophysiology*, 22(5), 561–567.
- Yuan, H., Yan, H. M., Xu, X. G., Han, F., & Yan, Q. (2007). Effect of heartbeat perception on heartbeat evoked potential waves. *Neuroscience Bulletin*, 23(6), 357–362.
- Zhang, Z. H., Dougherty, P. M., & Oppenheimer, S. M. (1999). Monkey insular cortex neurons respond to baroreceptive and somatosensory convergent inputs. *Neuroscience*, 94(2), 351–360.