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MASTER THESIS

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for the degree of Master of Science

MECHANISMS OF INTEROCEPTIVE-EXTEROCEPTIVE INTEGRATION DURING CARDIO-AUDIO SYNCHRONY

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Résumé

English.

Synchronization between bodily signals and external stimuli enables more efficient interactions with our surroundings. Recently, Pelentritou et al. 2022 found that detection of omission in a sequence of standard sounds induces a deceleration of the cardiac rhythm when auditory stimuli were aligned with heartbeats but not when they were not. This interoceptive effect can be explained within the predictive coding framework with surprise response and interoceptive active inference or according to the dynamical coupling theory. To disentangle which one of these three theory is more likely to explain this phenomenon, we designed an auditory oddball experiment that modulates synchronicity of cardiac and auditory stimuli, regularity and type of the deviant stimulus. In addition, we run a detection task experiment to test for cardio-audio synchrony effect on the behavioral scale.
Our preliminary results indicate that cardio-audio synchrony effect is independent of regularity and type of deviant and has no effect on behavior. Hence, we suggested that the effect relies on a startled surprise response.

Keywords. cardio-audio synchrony, dynamical coupling, interoceptive inference, predictive coding, surprise effect, EGG, ECG, pupillometry, EDA, respiration

Français.

L'harmonie entre les signaux corporels et les stimuli externes nous permet d'interagir de manière plus appropriée avec notre environnement. Récemment, Pelentritou et al. 2022 a découvert que la détection d'une omission dans une séquence de sons répétés provoque un ralentissement du rythme cardiaque lorsque les stimuli auditifs sont alignés sur les battements cardiaques, mais pas lorsqu'ils ne le sont pas. Cet effet interoceptif peut s'expliquer dans le cadre du codage prédictif par une réponse de surprise et un processus d'inférence active, ou bien selon la théorie du couplage dynamique. Pour déterminer laquelle de ces trois théories est la plus susceptible d'expliquer ce phénomène, nous avons mené une expérience ”Oddball” auditive au cours de laquelle nous avons fait varier la synchronisation des stimuli cardiaques et auditifs, la régularité et le type de stimulus. De plus, nous avons réalisé une expérience de détection de déviant avec ce même design expérimental pour tester l'effet de synchronie audio-cardiaque à l'échelle comportementale. Nos résultats préliminaires indiquent que l'effet de synchronisation audio-cardiaque est indépendant de la régularité et du type de stimulus déviant, et n'a aucun effet sur le comportement. Nous proposons alors que cet effet repose sur une réponse cardiaque de surprise précoce.

Mots clés. synchronisation audio-cardiaque, couplage dynamique, inférence intéroceptive, codage prédictif, effet de surprise, EGG, ECG, pupillometrie, EDA, respiration

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Thank you.

1. Recontextualization

For the final internship of my Master years, I looked for a research project in consciousness which is the thematic that I would like to study as a Ph.D student. One of my other criteria was to find a project in which I could use both the biomedical knowledge that I acquired through my undergraduate years and my cognitive science expertise. I heard about the Physiology of Cognition lab which investigates consciousness by mean of bodily signals measures thanks to a Belgium friend met at one of the conferences that we organized with "Neuronautes", the association of neuroscience in which I am a member of. As I was profoundly intrigued by the studies of the laboratory, I contacted Pr. Athena Demertzi to ask about a possible collaboration as part of an internship. Our aims converged as Matthieu Koroma, one of the post-doctoral researcher specialized in sleep, also looked for an intern to help him in his new project about cardio-audio synchrony. A first virtual meeting with Matthieu and Athena encouraged me to move to Belgium and help them investigate such a strange phenomenon that is the cardiac deceleration to omission that occurs only when heart and sounds are synchronized. I was well received by the lab and rapidly integrated into the team.

My internship was planned to last from February to June. As it was a pretty short period of time, one objective was to efficiently organise my time in order to submit my thesis at the end of May. Thus, during the first two months, I made several bibliographical research about the cardio-audio topic in order to write the introduction and the methodological part of my thesis. In the mean time, I also studied the python program about cardio-audio closed loop stimulation provided by Matthieu Scheltienne after discussion with our Swiss collaborators Andria Pelentritou and Marzia De Lucia whose previous work constitutes the foundation of our project. As I had little knowledge about python at the beginning of the internship and our time was short, I did not manage to fully adapt the program to our needs and the programming of the experiment was handover to Matthieu. One mistake from my part was to not ask for help early enough when something was out of my range of understanding. Though, I learned a lot about python and git by working on my own. Previously to the internship and also during the first months, I also helped designing the experiment as the global procedure was conceived but not thought in details.

We finished to design and program the behavioral and physiological experiments early April but as the equipment of the facility was already booked for other team project, we only could begin the acquisition at the middle of the month. In the mean time, I begun to prepare a poster to present to the BAPS annual meeting, continue to work on minor methodological details of the experiment and add my contribution to the pre-registration that we wanted to submit before the start of the acquisition. I also had the opportunity to help running a sleep deprivation and an anesthesia experiment.

The working environment of the lab offered many opportunities to learn new things collaboratively. Throughout the course of my internship, I had the chance to assist to different conferences about sleep, altered state of consciousness, hallucinations and mind blanking as they were frequently organized and proposed to all. Moreover, every member of the GIGA CRC, which is the bigger institution for which the physiology of cognition lab is only a part of, were very welcoming and prone to help and answer questions. I learned a lot about team management and team bonding and was very pleased to be part of group processing sessions during which we could meta cognitively think and talk openly about how to improve teamwork.

My work from the middle of April to the middle of May was to recruit participants by posting messages on student groups and via the University of Liege network, to organize the planning of testings, assure the payment, the signature and the completion of the FR-MAIA questionnaire and run the two experiments with Matthieu and all by my own. Thanks to that, I learned to administratively be organised and set up EEG, ECG, EDA, pupillometric and respiratory equipment. In parallel, I helped formatting the behavioral data on python, I analyzed them on R and interpreted the results while Matthieu worked on processing the ECG and EEG data and checked for delays that could hinder our experiment. I then proceed to the statistical analysis of the ECG data. As so, I acquired a solid skills base on data analysis and plotting using R. Finally, I went to Mons to communicate our results with a poster and submitted my thesis in time.

As short as it was, my internship experiment within the GIGA CRC in vivo Imaging team taught me to adapt myself to a new working environment and a new country, work collaboratively especially on programming, use my theoretical knowledge for more practical purposes and get out of my native language comfort zone. My major achievements during this internship was to reconcile myself with programming and communicate my results in English during the BAPS event.

I meta cognitively also pointed out working skills in which I would like to improve such as my ease to communicate orally in English. I would also like to learn how to organize my time better in order to be more efficient and I would like to try holding an experimental project all by myself as I really enjoyed working in the research field. To this end, I aim at pursuing my education with a Ph.D in the near future.

2. Introduction

Signals from inside our body shape how we perceive and react to our environment. Cardiac rhythm but also gastro-intestinal tract have their own intrinsic oscillatory electrical activities that influence brain and cognition (Azzalini, Rebollo et Tallon-Baudry 2019 ; Hsueh et al. 2023). More specifically, heart plays an important role in emotions (Pfeifer et al. 2017 ; Adelhöfer, Schreiter et Beste 2020), bodily perception for self-consciousness (Tsakiris, Jiménez et Costantini 2011 ; Aspell et al. 2013 ; Suzuki et al. 2013 ; Heydrich et al. 2018), social perception (Azevedo et al. 2017) and perceptual processes (Saxon 1970 ; Sandman et al. 1977 ; Al et al. 2020). Nevertheless, the mechanisms by which cardiac activity is integrated with sensory signals remain poorly understood.

Investigations into our ability to process cardiac activity in reference to external signals have majorly been studied with the Heartbeat detection task (HDT) (Brener, Liu et Ring 1993 ; Schneider, Ring et Katkin 1998 ; Ring et Brener 2018). In this task, participants are asked to determine whether sequences of tones are synchronous or not to their perceived heartbeat. This exercise that includes both the integration of internal and external signal has proven to give valid evaluation of our perceptual sensitivity to our cardiac activity, also called cardiac interoception (Ring et Brener 2018). Over the last decades, different studies have recorded neural activity during HDT with measures of heartbeat evoked potentials (HEP), i.e. the averaged electrophysiological response of the brain time-locked to heartbeats, to demonstrate the link between cardiac interoception and the neural processing of heartbeats (Pollatos et Schandry 2004 ; Pollatos, Kirsch et Schandry 2005 ; Mai et al. 2018). Recordings of HEP during passive detection of sound omissions occurring within sound sequences were conducted in parallel to investigate interoceptive processing without deviant sound contamination (Wacongne et al. 2011 ; Chennu et al. 2016).

The next step forward in the study of the integration of cardiac activity into perceptual processing came from the real-time closed-loop stimulation of sounds depending on the occurrence of heartbeat. Based on these studies, it was demonstrated that the timing of sounds relative to heartbeats modulated auditory processing as measured by HEP responses (Elk et al. 2014). By analyzing the brain responses to sound sequences presented either synchronously or asynchronously with the online detection of heartbeats, several studies have demonstrated that HEPs and brain responses to omitted sounds were both amplified when sounds were presented in synchrony with cardiac signals, thus demonstrating the integration of cardiac information and sensory signals into neural processing (Pfeiffer et De Lucia 2017 ; Banellis et Cruse 2020). Moreover, Pfeiffer et De Lucia (2017) and Pelentritou et al. (2022) showed that the timing between auditory inputs and cardiac activity also influences cardiac activity in return. By comparing cardiac signals upon sound omission and standard sounds, they brought into light a deceleration of cardiac rhythm in response to omission deviants only if heart and auditory cues were synchronized, but not when they were desynchronized, hence highlighting an inter modulation of external auditory stimuli and internal cardiac activity.

To account for these bidirectional influences between the body and the brain, an influential framework that has been put forward is predictive coding. This model considers the brain as a hierarchical inferential machine whereby high level neuronal layers generate predictions based on afferent signals from low level layers to confront them with ongoing inputs (Rao et Ballard 1999). Mismatches between predictions and new incoming sensory inputs are conveyed to higher layers as prediction errors, leading to retroactive loops of predictions that dynamically update perception. Predictive coding outlines how predictions benefit perception by allowing for faster and more accurate detection (Anllo-vento 1995 ; Mangun 1995), lower detection thresholds (Hawkins et al. 1990 ; Luck et al. 1994 ; Correa, Lupiáñez et Tudela 2005), as well as computation of temporal regularities in sensory processing (SanMiguel, Saupe et Schröger 2013).

These predictive operations can propose an explanation for the cardiac deceleration upon omission during cardio-audio synchrony as part of a surprise response to deviant stimuli (Graham 1979 ; Graham et Clifton 1966 ; Bradley 2009 ; Pfeiffer et De Lucia 2017). Indeed, when facing unexpected event, two types of reactions can occur : either for perception by orienting all resources to analyze the situation (Sokolov 1963 ; Skora, Livermore et Roelofs 2022), or mentation and action for defence reflexes to happen depending on the urgency to react. For instance, when an unpredicted event occurs during an oddball experiment, the brain might not consider it threatening enough in the context of the experiment to trigger defence processes but peculiar enough to mobilize its resources into perceptual processes to detect and assess what is happening. This phenomenon is commonly reflected in terms of a slowing down of bodily activity, including cardiac rhythm, to favor perceptual processing (Skora, Livermore et Roelofs 2022). One hypothesis for the heart deceleration during cardio-audio synchrony is thus that prediction processes are stronger when different modalities are coupled, and so generate more noticeable deceleration effect on the heart when cardiac and auditory modalities are synchronized.

Another possible explanation to account for the cardiac deceleration, called interoceptive active inference, also stems from predictive processing and puts a stronger focus on the influence of brain processes on bodily signals (Friston, Daunizeau et Kiebel 2009 ; Seth et Friston 2016). According to this framework, prediction errors raised by the confrontation of prediction and inputs can be minimized either through perceptual inference by iterative updating of expectations to match unexpected signals or by performing voluntary or automatic actions including visceral control to match expectations (Friston 2009 ; Seth et Friston 2016 ; Martin et Pacherie 2019 ; Banellis et Cruse 2020). Thus, from the embodied perspective whereby both perception and action can reduce prediction errors, cardiac activity would be slowed down upon sound omission by the brain to match the timing of external stimuli when both signals are synchronized, resulting into the deceleration effect upon omission found only during cardio-audio synchrony (Pelentritou et al. 2022).

Finally, an alternative explanation that bypasses the need for predictive systems called dynamical coupling also can be considered. The dynamical coupling model refers to alignment of multiple systems to external oscillator (Lakatos, Gross et Thut 2019 ; Banellis et Cruse 2020 ; Greenfield et al. 2021 ; Palmer et Demos 2022). In this model, auditory stream, brain and heart are considered as three distinct oscillators that couple with one another unidirectionally (entrainment) or bidirectionnaly (synchronization). External sounds thus entrain the brain to synchronize its oscillations to the rhythm perceived and the heart to beat at the same pace as the perceived rhythm. By leaning towards the synchronicity between the body and external stimuli, metabolic cost of activities can be reduced and performance can thus be enhanced (Terry et al. 2012 ; Lim et al. 2014). For instance, walking pace, dancing and sport activity have been proven to tend toward synchronization with the grasped rhythm of music (Large 2000 ; ich 2008), by which cardiac activity is either reduced or accelerated according to the music tempo (Bernardi et al. 2009 ; Van Dyck, Buhmann et Lorenzoni 2021). The cardiac deceleration upon omission can hence be elucidated by the coupling between sounds and cardiac activity, upon which an omitted sound entrains the deceleration of cardiac rhythm.

Our study aims to specify the contribution of each model in explaining the mechanisms of cardio-audio synchrony at a behavioral and physiological levels. To do so, we will compare predictions of behavioral responses and physiological signals including brain, heart, respiration, electrodermal and pupil activities in an oddball experiment with sounds and deviants presented either synchronously or asynchronously with cardiac activity. We will manipulate variables such as the regularity of occurrence of deviants (regular or random), as well as the type of deviant (rare tone or omissions) to test the different models. As behavioral responses can influence physiological recordings, we will record reaction times and multi-modal physiological responses to deviants in two separate experiments following the same design. In addition, as many studies on interoception showed an influence of interoceptive sensitivity across participants on cognition (Herbert, Pollatos et Schandry 2007 ; Tsakiris, Jiménez et Costantini 2011 ; Suzuki et al. 2013 ; Sel, Azevedo et Tsakiris 2017), we will ask participants across both experiments to discriminate which are the sound sequences presented in synchrony with heartbeats and to give their subjective evaluation of interoceptive awareness by completing the FR-MAIA questionnaire (Willem et al. 2022).

Our hypotheses according to each model and parameter investigated were the following :

i) Behavioral effects

First, our behavioral experiment will investigate the behavioral correlates of cardio-audio synchrony. Considering that cardio-audio synchrony can be responsible for behavioral benefits in sensory detection, we expected overall faster reaction times in conditions in synchrony compared to out of synchrony. In line with the predictive coding framework, we also expected faster reaction times when deviants were presented regularly compared to when they were presented randomly as they would be awaited, as well as when they were rare tones compared to omissions as they would be more easily detected. Unexpected results when comparing each couple of regularity and type of deviant would be considered as an evidence of active inference mechanisms since it would reveal an intervention of the participants to boost his performance with thoughtful strategies.

ii) Cardiac signals

For all models, we expect a modulation of cardiac activity by the synchrony of sounds stimulation with the cardiac rhythm. In the case where cardiac deceleration is modelled as a surprise response, we expect a deceleration when deviants are both rare tones and omissions with an enhanced effect when the deviant occurs randomly as it would be more surprising than if it occurs regularly (1). Considering the active inference hypothesis, we can anticipate a cardiac deceleration only with omissions to match the slowing down of the sound sequence, and a stronger deceleration for random condition compared to regular condition as the prediction error would be in that case stronger as well. Finally, dynamical coupling theory also suggests that a cardiac deceleration will only be found with a sound omission compared to the rare tone but no effect of regularity should be expected, as there are no predictive mechanisms at play in that case.

iii) Other physiological signals

Physiological Predictions			
Models	Type of deviant (RARE TONE or OMISSION)	Regularity (REGULAR or RANDOM)	Other modalities
Surprise Response	x	Random>Regular	EEG,EDA,pupil size
Active Inference	Omission>Rare	Random>Regular	EEG
Dynamical Coupling	Omission>Rare	x	EEG, Respiration

Table 1 – *Interaction effects on cardiac signals and other physiological modalities predicted according to our different mechanistic explanations of cardio-audio synchrony. EEG : electroencephalography, EDA : Electrodermal activity*

Other physiological signals should also enlighten us about the mechanisms involved in cardio-audio synchrony. For instance, cerebral responses would be rather evidenced through a modulation of evoked potentials to deviants (1) for surprise responses and heartbeat evoked potentials for active inference since both rely on predictive processes of sensory and interoceptive mismatches, while cerebral modulations should rather be evidenced in evoked spectral activity according to dynamical coupling that relies on oscillatory coupling. As active inference has a more specific action on automatic organs, we should only expect a cardiac deceleration for active inference whereas electrodermal activity, pupil size and brain activity should be more strongly modulated in surprise response. On the other hand, because respiratory rhythm is more tightly coupled with cardiac activity than other physiological signals recorded, we can expect an effect of sound omission on respiratory measures that follows that of cardiac modulations for dynamical coupling, and less so for the other physiological signals.

iv) Interoceptive ability

We have two different measures of interoception : FR-MAIA which reflects interoceptive awareness as an individual trait and synchronization judgments which reflects interoceptive awareness during the experiment. As it has been demonstrated by several studies that HEPs were modulated by interoceptive sensitivity (Schandry, Sparrer et Weitkunat 1986 ; Katkin, Cestaro et Weitkunat 1991 ; Pollatos et Schandry 2004 ; Pollatos, Kirsch et Schandry 2005), we expect individuals with high interoceptive abilities to build stronger predictions and thus to show more important effects of synchronization. Nevertheless, following previous studies, we expect no interoceptive awareness of the synchronous condition to be found (Pfeiffer et De Lucia 2017 ; Pelentritou et al. 2022). However, if such an effect was found, it would be of interest to assess in an exploratory way whether awareness of the synchronous vs. asynchronous conditions correlates with trait interoceptive awareness and modulates our behavioral and physiological effects.

3. Material and Methods

3.1. Participants

Healthy adults (18 to 35 years old), equally balanced in gender and without history of cardiac nor mental disorders nor uncorrected auditory deficits, were recruited from the GIGA CRC's team. To estimate our sample size, we used a GPower computation (A priori : ANOVA : Repeated measures, within factors), effect size f : .25 (middle effect), error : 0.05, groups : 1, correlation among repeated measures : 0.5, non sphericity correction : 1 aiming at power 0.95 with 50 measurements for the physiological experiment. This resulted in a total sample size of 8 for the behavioral experiment and 34 for the physiological experiment. For purposes of possible attrition, we submitted to run 10 participants for the behavioral experiment and 40 for the physiological experiment.

The study was approved by the Ethics Committee of the University Hospital of Liege and all participants provided written informed consent prior to participation. Participants were informed that they are free to abort the experiment anytime without facing negative consequences. Upon completion of the physiological experiment, participants received a monetary compensation of 50€. In line with the Regulation (EU) 2016/679 of the European Parliament and Council from April 27th, 2016, data obtained during the experiment were anonymized and handled confidentially. The code of conduct complied with ethical standards laid down in the 1964 Declaration of Helsinki.

3.2. Material

Stimuli were 50ms pure sounds sampled at 44100Hz generated with the ”Sound” function with the Psychopy module of Python (Peirce et al. 2019). Stimuli were either standard (80%) or deviant of a different frequency (400Hz vs. 800 Hz, counterbalanced across participants), depending on the condition tested. Stimuli were delivered through earphones. EEG and ECG data were acquired using a 64-electrodes actiCap headcap and an actiCHamp amplifier at a sample frequency of 500 Hz (BrainProducts). Pupillometry was recorded with a Phasya recording system at a sample of 120 Hz (Phasya Drowsimeter R100). All the other physiological signals were collected using the BIOPAC (MP160) system. For EDA, two electrodes were positioned on the pulp of the right index and middle fingers and for respiration, a belt girdled the thorax of the participant.

3.3. Experimental Design

The experiments followed a 3x2 factorial within-subject design with cardio-audio synchronization, type of deviant and regularity as independent variables. Sounds were played either synchronously (SYNC) or asynchronously (ASYNC) with the heartbeat. Type of deviant was either omission (OMISSION) or rare tone (RARE TONE). The deviant either appeared every 5 sounds (REGULAR) or between 3 or 7 sounds (uniformly distributed, RANDOM). In the behavioral experiment, the outcome measure was the reaction times to the detection of deviants. In the physiological experiment, outcome measures were modulations of cardiac, electroencephalographic, electrodermal, respiratory rhythm and pupil size responses to the onset of the deviant to test for physiological reactions. For both experiments, interoceptive awareness was assessed with the FR-MAIA questionnaire filled before the experiment and after each part with the cardio-audio synchrony discrimination question.

3.4. Procedure

During the experiment, participants were tested for each combination of conditions. Experiment started with four trials of training during which sounds were presented at a fixed sound-to-sound interval (isochrony) computed with cardiac recordings from a preceding baseline trial at rest (1). Each trial presented a different combination of regularity and type of deviant to the participant. Following the training session, participants were tested on the four different parts of the experiment. Each part represented a different combination of regularity and type of deviant conditions (fully randomized and counterbalanced across participants). For each part, participants started with a baseline block at rest (5 minutes for the behavioral experiment, 10 minutes for the physiological experiment) in order to collect interbeat (RR) intervals necessary for the generation of the asynchronous condition. It was followed by two blocks with the first beginning by either the synchronous or asynchronous condition and the second block being the other synchronisation condition. For each block of trials, participants were instructed to listen to the sequence of sounds (503 sounds in the physiological experiment, 253 in the behavioral experiment), from which 20% were deviants. The last three stimuli of all blocks were always standard sounds to avoid awkward appearance of deviant at the end of a sequence. In addition, participants were required to press a button as soon as they detected a deviant stimulus in the behavioral experiment only. At the end of each block, participants rated on a six points Likert's confidence scale whether the synchronous or asynchronous was presented first during the block (1 : very confident SYNC, 6 : very confident ASYNC). Lastly, an open ended interview during which we asked the participant if he used any particular strategy to differentiate synchronous and asynchronous blocks allowed us to conclude the experiment.

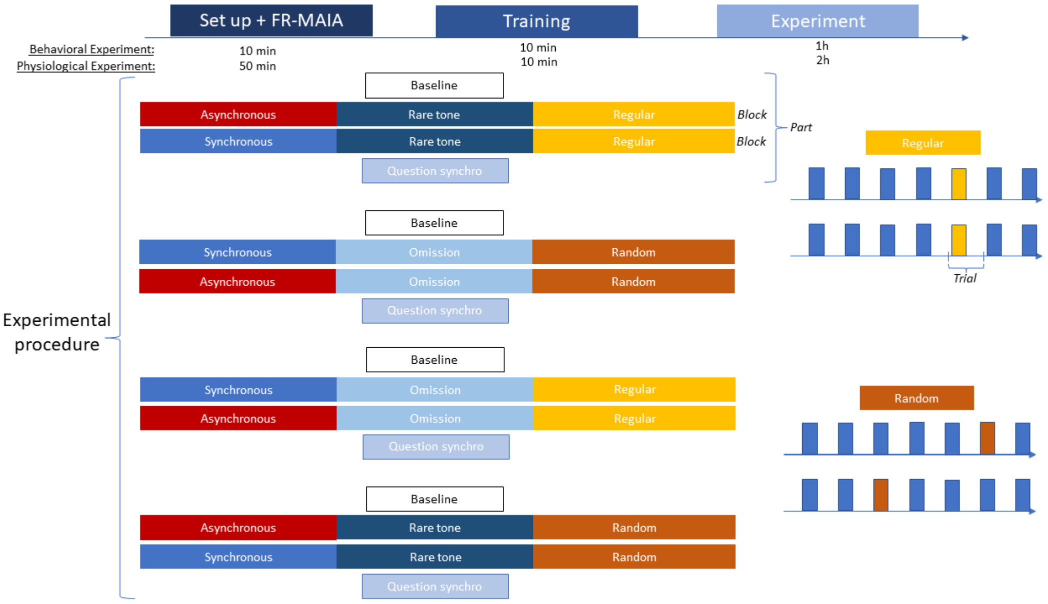

FIGURE 1 – *Experimental procedure of behavioral and physiological experiments*

3.5. R peak detection

Temporal onsets of sounds were defined based on the online analysis of real time raw ECG recordings using an open-source Python script (Scheltienne 2022). R-peaks were detected when the signal satisfied the peak detection criteria (height percentage = 97,5%, prominence = 500, width = NONE, interbeat interval = 500ms) over the last 4 seconds of stream acquired. When necessary, the detection criteria to ensure accurate R-peak detection were individually adapted prior to the experiment. In the synchronous blocks, sounds were triggered upon R peaks detection with a R peak to sound onset (RS) delay of 52.2 ± 2.6 ms across participants in the behavioral study and 49.4 +/- 1.3 ms in the physiological study (see 9 for average and standard deviation of median values for RS delays across participants). In the asynchronous condition, interstimulus intervals were determined by randomizing the heartbeat intervals after detecting R-peaks from the ECG signals of the preceding baseline trial following Pfeiffer et De Lucia (2017). Specifically, interbeat intervals were randomly selected and shuffled to give rise to a pseudo-random sequence mirroring natural cardiac rhythm of participants (2). This resulted in a more variable RS delay (sync : 15.13±3.88ms vs. async : 280.07±44.95 ms, post-hoc emmeans test : $\beta=265$, $SE=4.24$, $p<.0001$) and Sound to R-peak (SR) delay than for the synchronous condition (sync : 81.53±30.27 vs. async : 277.58±43.21, post-hoc emmeans test : $\beta=196$, $SE=3.7$, $p<.0001$) (see 9.C,D). Baseline trials lasted 10 minutes to collect at least 503 RR intervals for the physiological experiment and 5 minutes to collect at least 253 RR intervals in the behavioral experiment and were incremented by step of 30s if participant's cardiac rhythm was too low to record enough RR intervals.

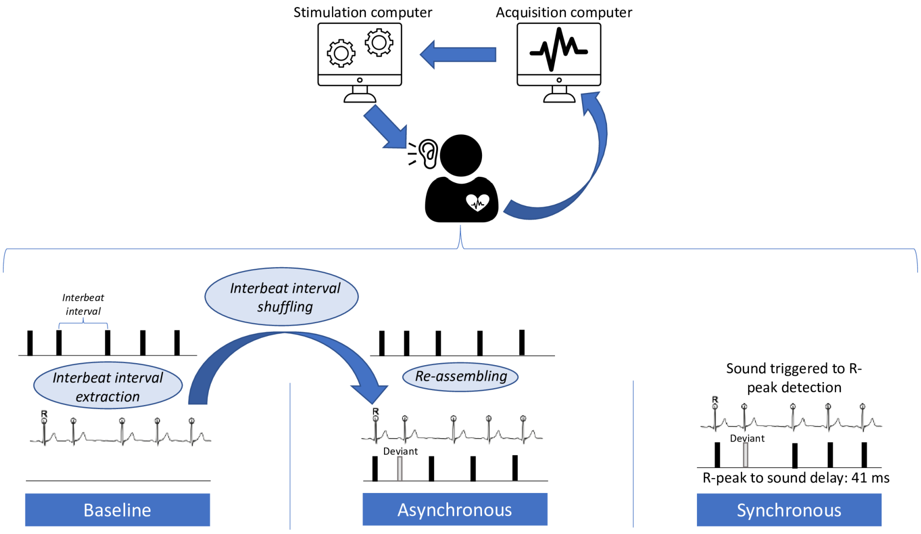

FIGURE 2 – *Closed loop stimulation to generate synchronous and asynchronous conditions. Synchronous sequences were built directly by triggering a sound to each heartbeat detected. Asynchronous sequences were created by shuffling interbeat intervals collected during previous baseline block*

3.6. Behavioral analyses

Reaction times for deviant detection were extracted for each trial as the difference between the onset of the last deviants and button press. Reaction times above three standard deviations above the mean of the total distribution per subject were removed. Responses to the discrimination task between synchronous and asynchronous blocks were computed by recording correct responses as positive values (i.e., 0.33 for random, 0.66 for unsure, 1 for certain) and incorrect responses as negative values (-0.33 for random, -0.66 for unsure, -1 for certain). Response scores for each participant were computed by averaging responses across blocks for each participant. For the MAIA questionnaire, the total score was computed according to standard procedure (Willem et al. 2022, D).

3.7. ECG preprocessing

ECG data was preprocessed offline using the open-source Python neurokit2 package (Makowski et al. 2021). ECG were cleaned with a 0.5 Hz high-pass butterworth filter (order = 5), followed by powerline filtering(powerline = 50). R-peaks were then extracted using the Pan-Tompkins method over each blocks for continuous analyses and each epochs around sounds(-3,6s) for evoked analyses(Pan et Tompkins 1985). For evoked responses, R-peaks were extracted. Interbeat intervals around sound onset below 600 ms and above 1200 ms were excluded from analyses. For continuous analyses, we computed interbeat interval (RR) and the standard deviation of RR as a proxy for heart rate variability (HRV). For evoked analyses, interbeat interval (RR) (evoked HR) before and after the onset of tones and deviants were extracted and compared across conditions. Interbeat intervals around sound onset below 600 ms and above 1200 ms were excluded from analyses to avoid contamination by false positive and misses of R-peak detection.

3.8. EEG processing

EEG data was preprocessed following a standard procedure using the MNE package version 0.23.0 (Larson et al. 2023 ; Gramfort et al. 2013). Signals were bandpass filtered from 0.1 to 45Hz and a notch filter was applied at 50Hz. For evoked responses, epochs from -100 to 500 ms around events was extracted, bad epochs for which mean voltage of the channel has significant deviances from the mean (+/- 100 microV absolute differences) was rejected following Pfeiffer et De Lucia (2017). Epochs were then averaged over the trials of the same condition for each channel within participant and grand average was computed (Pfeiffer et De Lucia 2017).

3.9. Statistical Analysis

All mixed model analyses were computed using the lme4 package in R (Bates et al. 2018). For the behavioral experiment, general mixed model was applied with conditions as fixed effects and subjects as random effects. Gamma distribution and inverse link function was used to normalize reaction time data. Participant's data which do not follow a gamma distribution with inverse link function were considered as outliers. For statistical significance of the difference between pairs of conditions, we carried out simple effects post-hoc test using the emmeans function. Response score and FR-MAIA questionnaire scores were then added as co-factor of the model to test for the effect of interoceptive abilities. Non parametric wilcoxon test for responses scores against 0 were used to assess the ability of correctly guessing which block was synchronous and asynchronous. Kendall correlation test was used as post-hoc tests for correlation between the FR-MAIA score and responses scores.

This project has been pre-registered before data acquisition on the OSF page of the project : https://osf.io/6fvuw/

4. Results

4.1. Reaction times

As planned according to our power analyses, 10 healthy adults were included in the behavioral version of our study (age = 24.8±2.4, 5 women).

First, we investigated how synchrony, regularity and type of deviant impact reaction times when detecting a deviant. To do so, we fitted a generalized linear mixed model (GLMM) with inverse gamma regression to predict RT with the three conditions as fixed effects and subject as random effect. The analysis revealed a main effect of type of deviant (β=0.07, SE=0.02, p<2e-16) and regularity (β=0.22, SE=0.02, p<2e-16) and an interaction effect between both deviants and regularity (β=-0.16, SE=0.03, p<1.28e-8) but no effect of synchrony(β=0.008, SE=0.028, p=0.65). Likelihood test ratio comparing the full model and the same model without synchrony as co-factor confirms that the two models are equivalent and that synchrony is thus not a predictor of RT (χ^2=3.86,p=0.43).

Post-hoc pairwise comparison analysis for each deviant type and regularity combination revealed significant differences for each couples of conditions. Random omissions were detected slower than random rare tones because they were less salient and needed more time to process(β=-0.05, SE=0.01, p=0.0003) (3). On the contrary, we found that participants were faster for regular omissions than regular rare tones as they often pressed by anticipation before the real occurrence of omissions(β=0.10, SE=0.02, p<0.0001) (3). RT on random omissions were slower than regular omissions due to prediction processes(β=-0.23, SE=0.01, p<0.0001) and random rare tones were also detected slower than regular rare tones(β=-0.18, SE=0.01, p<0.0001) (3). Overall, these results demonstrate a strong prediction effect modulated by the type of deviant which is inline with the interoceptive active inference hypothesis.

In a second time, we wanted to verify if better speed performances were not depending on the correct deduction of synchrony. To this end, we added response scores to the synchrony questions as a predictor of RT into our GLMM. Model comparison analysis revealed that response scores weren't good predictors of mean RT and so that interoceptive awareness didn't affect the speed of detection of deviants (χ^2=2.66,p=0.62). Finally, as we found no effect of synchrony and cardio-audio interoception on detection task, we expected MAIA scores to not influence RT either. We indeed found that interoceptive ability was uncorrelated to the detection task as likelihood test ratio on GLMM with and without MAIA as predictor of RT showed that interoceptive ability doesn't influence response times (χ^2=3.86,p=0.43). This shows that interoceptive abilities did not impact behavioral performance in our detection task.

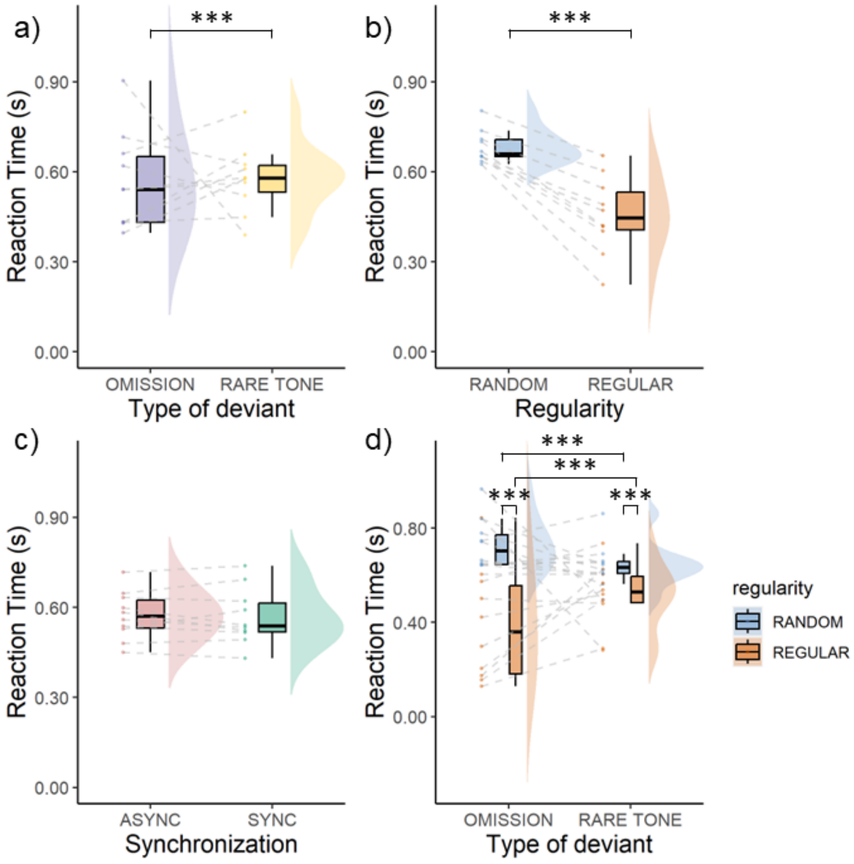

FIGURE 3 – *Reaction times to deviant according to a) type of deviant, b) regularity, c) synchronization, d) regularity and type of deviant. GLMM analysis revealed a main effect of type and regularity of the deviant with an interaction effect between them but no effect of cardio-audio synchrony.*

4.2. Cardiac signals

20 healthy adults on the 40 planned were recruited for the physiological version of the study, from which 3 were excluded due to technical problems during the acquisition, resulting in the inclusion of 17 participants (age = 22.3±2.7, 9 women).

To show that the overall variations of heart rate was not a confounding for our cardiac results, we first checked that RR intervals were not significantly changing across baseline, synchronous and asynchronous blocks (4). Linear mixed model analysis with subject as random effect showed no main effect of synchrony (β=-0.003, *SE*=0.018, *p*=0.86) on RR intervals. This was also true for heart rate variability (β=4.55, *SE*=3.17, *p*=0.15) (4).

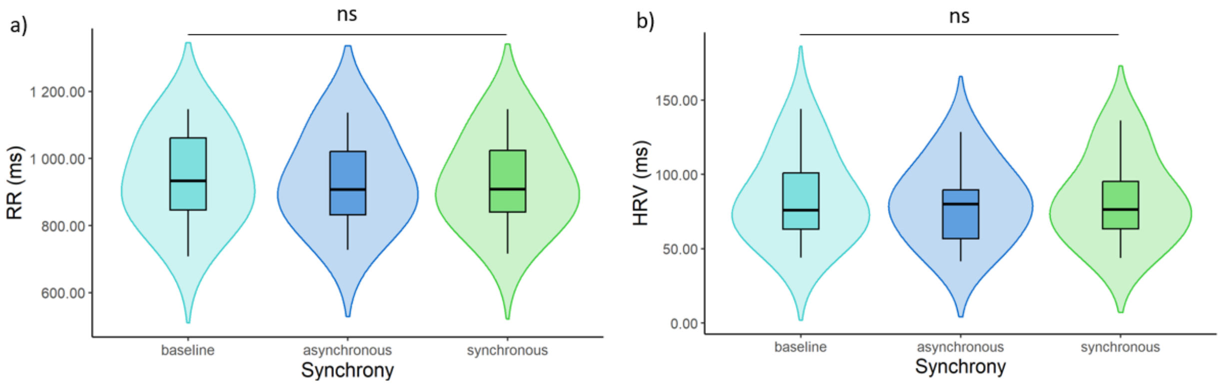

FIGURE 4 – *Consistent distribution of* (*a*) *interbeats intervals* (*RR*) *and* (*b*) *heart rate variability throughout baseline and the two conditions of synchrony.*

We then tested whether the occurrence of auditory deviants modulated cardiac activity. To do so, we normalized interbeat intervals by the average RR intervals before deviants for each condition. Linear mixed model effects revealed no main effect of deviant type (β=-9.640e-04, *SE*=2.792e-03, *p*=0.73) or regularity (β=-1.162e-03, *SE*=2.792e-03, *p*=0.68) but a main effect of cardio-audio synchrony (β=-8.819e-03, *SE*=2.792e-03, *p*=0.0016). Position to the deviant was near significance (β=-6.789e-03, *SE*=3.948e-03,*p*=0.086) and was kept in the model for further analyses. We thus removed regularity and deviant type as co-factor of our mixed model.

The main effect of synchrony was reinforced within this model (β=0.011, *SE*=0.001, *p*=1.33e-15) and an interaction effect between position and synchrony emerged especially between positions RR-1 and RR0 (β=0.008, *SE*=0.003, *p*=0.003) and positions RR0 and RR+1 (β=-0.010, *SE*=0.003, *p*=0.0006). For the asynchronous condition, post-hoc tests showed significant acceleration of cardiac rhythm after the deviant appears at RR+1 (β=0.011, *SE*=0.002, *p*=0.004) and RR+2 (β=0.009, *SE*=0.002, *p*=0.027). For the synchronous condition, we found a faster deceleration of cardiac rhythm with a increase of RR intervals at RR0(β=-0.012, *SE*=0.003, *p*=0.0005) but also a faster return to normal as RR+1 wasn't found different than RR-1 (β=-0.004, *SE*=0.003, *p*=0.76). We then compared RR intervals of the synchronous versus asynchronous condition at each position. We found significant differences at position RR0 (β=-0.017, SE=0.003, p<0.0001), RR+1 (β=-0.015, SE=0.003, p<0.0001) and RR+2(β=-0.013, SE=0.003, p=0.0001) (5). Overall, we revealed that the synchrony effect relies on a brief deceleration of cardiac rhythm when the heart is synchronized to the sound and a steady acceleration when it is not beating in harmony with sounds.

As our model predictions are based on variation of the cardiac deceleration across type and regularity of deviants, we also report results clustered accordingly. With the same method as with the main effect of synchrony, we computed a LMM of RR predicted by position and synchrony for each group of sub results. We found a main effect of synchrony for each pair of conditions (Random Omission : β=0.009, SE=0.002, p=0.0002 ; Regular Omission : β=0.009, SE=0.002, p=0.0002 ; Random Rare Tones : β=0.01, SE=0.003, p=6.42e-05 ; Regular Rare Tones : β=0.01, SE=0.003, p=0.0003). Post-hoc comparisons between synchronous and asynchronous failed to reach significance for random omission at each position around the deviant (RR0 : β= -0.01, SE=0.005, p=0.28 ; RR+1 : β= -0.01, SE=0.005, p=0.07 ; RR+2 : β= -0.01, SE=0.005, p= 0.27) but was significant for regular omissions at RR0 (β=0.02, SE=0.006, p=0.02), with random rare tones at RR0 (β=-0.02, SE=0.006, p=0.02) and at RR+1 (β=-0.02, SE=0.006, p=0.04) and with regular rare tones at RR0 (β=-0.02, SE=0.006, p=0.05) (6).

To test for interoceptive ability on cardiac effect of synchrony, we added first response score and then MAIA to our predictive model. LMM analysis with response score as predictor revealed that RR intervals are unrelated to how well participants answered to the synchrony question (β=0.001, SE=0.002, p=0.46). Nevertheless, comparison of LMMs with and without MAIA scores revealed a relationship between individual interoceptive ability and RR intervals (χ^2=50.05,p=3.531e-10). More precisely, LMM analysis revealed an interaction effect of synchrony with MAIA scores (β= 2.003e-04, SE=6.988e-05, p= 0.004).

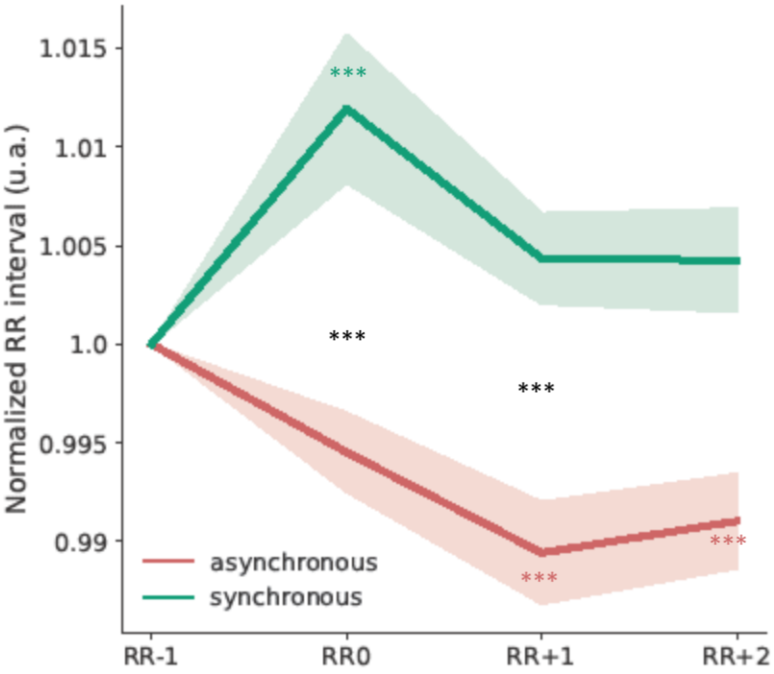

Figure 5 – *Normalized RR intervals around the appearance of the deviant.*
*Post-hoc emmeans for significance testing of differences at each position with position RR-*1 *for asynchronous* (*** : $p<0.001$) *and synchronous conditions* (*** : $p<0.001$)*. Post-hoc emmeans for significance testing of synchrony differences at each position* (*** : $p<0.001$).

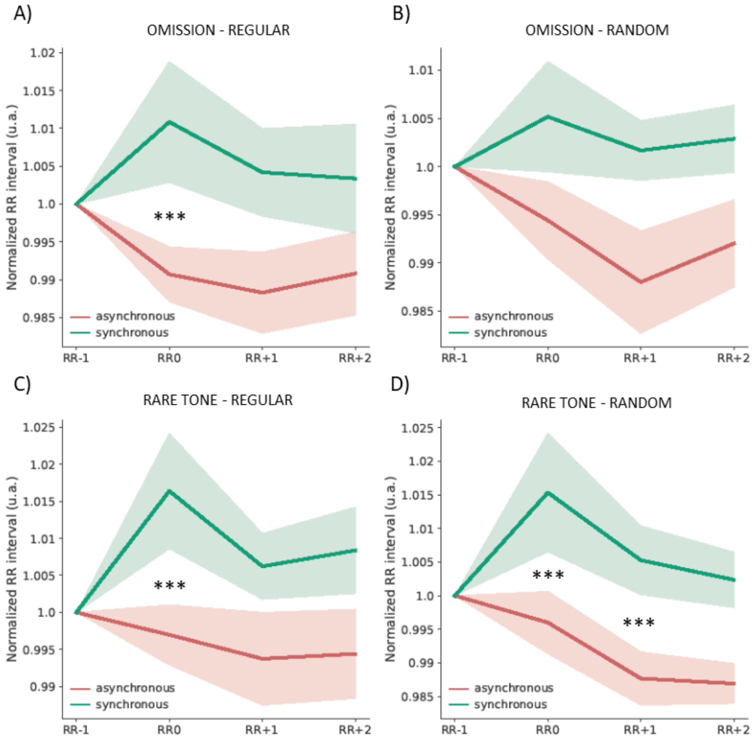

Figure 6 – *Normalized RR intervals around the appearance of the deviant for clustered data by regularity and type of deviant conditions.*
Post-hoc emmeans for significance testing of synchrony differences at each position (*** : $p<0.001$).

4.3. Interoception

To test whether participants were aware whether they were in a synchronous or asynchronous conditions, we calculated response scores for each question corresponding to the product of the exactitude (wrong answer : -1, right answer : 1) and the confidence in the answer (at chance : 1/3, uncertain : 2/3, certain : 1). In the behavioral experiment, participants were close to significance in their ability to appropriately guess above chance level which block was synchronous (0.18±0.71, effect size : r=0.274, non parametric Wilcoxon-test test against 0 : p=0.086). In the physiological experiment, participants were significantly better than chance (0.28±0.70, r=0.381 , p=0.002) (7). Mixed-model analyses revealed no significant effect of groups on exactitude of responses (β=-13.24, SE=11.60, p=0.25) nor confidence(β=2.97, SE=4.77, p=0.53), justifying to consider the two groups together. Overall mean response score for the combined data showed that they guessed above chance which block was synchronous. (0.25±0.70, r=0.342 , p=0.0003) (7). Post experience interviews with participants enlightened us about these results. Several participants mentioned that they controlled their breathing to either accelerate their cardiac rhythm and sounds at the same time in the synchronous condition, allowing them to spot it easily.

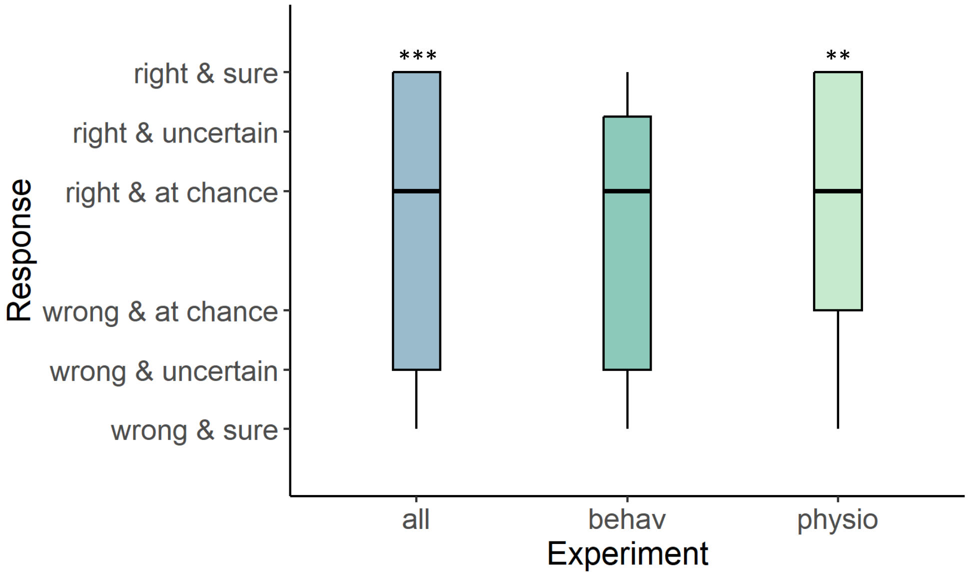

FIGURE 7 – *Response score for each experiment. Overall, participants guessed above chance which block was in or out of synchrony*

Finally, to test whether the ability to guess which condition was synchronous was related to explicit knowledge and trait-interoception ability, we tried to predict correct responses with a generalized linear mixed model (binomial link function). We found that neither confidence (β =2.51, SE=4.83, p=0.60) nor MAIA (β=3.47, SE=6.01, p=0.56) were good predictors of correct or incorrect guesses of synchrony. Therefore, we found no evidence that explicit awareness nor individual interoceptive ability contribute to percentage of correct guesses. We also found that MAIA doesn't correlate with response scores neither when comparing ranks with a Kendall correlation test (Kendall correlation test, r=0.17, p=0.22).

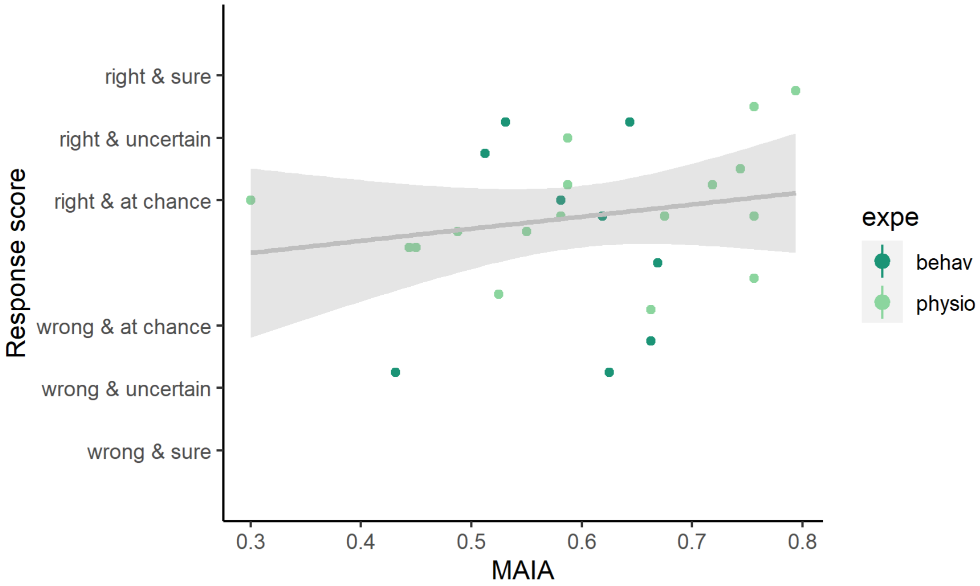

FIGURE 8 – *Distribution of response score by participant and MAIA scores. No correlation was found between interoceptive ability and interoceptive awareness during the experiment.* (*** : *p*<0.001)

4.4. Other physiological data

EEG data were pre-processed but still need to be checked and analysed (see 10). Other physiological signals were not yet processed nor analysed.

5. Discussion

Our study investigates the mechanisms and behavioral benefits related to the joint integration of bodily and external signals. More precisely, we tried to elucidate the underlying processes of the cardiac deceleration to omission found by a recent study of Pelentritou et al. (2022). To this aim, we conducted two auditory oddball experiments when modulating cardio-audio synchrony, regularity and type of deviant to measure physiological reactions to deviant with ECG, EDA, EEG, pupillometry and respiration and behavioral benefits in response time when detecting a deviant. We also questioned participants about their individual interoceptive ability with the MAIA and investigated their cardiac awareness during the experiment by asking them whether blocks of sounds were in or out of synchrony with their heartbeat.

Contrary to our predictions, our behavioral results show no particular benefits of cardio-audio synchrony on response time to deviant. These results go along with previous results of Banellis et Cruse (2020) and Delfini et Campos (1972) that showed that cardio-audio synchrony did not affect auditory detection tasks. It is noteworthy that Banellis et Cruse (2020) used a different method to generate the asynchronous condition by augmenting the R-peak to sound (RS) duration (early vs late RS delay) rather than randomizing the interbeat intervals. Furthermore, they asked their participants to respond if an omission was present or not at the end of a sequence rather than measuring the reaction time to this detection.

Moreover, similarly to Banellis et Cruse (2020), our findings were further supported by the fact that interoceptive awareness and interoceptive abilities as measured by MAIA don't contribute to participant performances at the external task of detection. Together, these results thus confirm a limited impact of cardio-audio synchrony on auditory detection. Regarding the effect of regularity and deviant types, we found as expected that both influenced behavioral responses. Regarding regularity, this can be explained by the fact that participants could anticipate the occurrence of deviants in the regular condition but not the random condition. Henceforth, they could focus and prepare their motor response way more efficiently than when the deviant comes irregularly. Regarding the type of deviant, this can be explained by the fact that a rare tone is a salient signal that can be faster detected than an omission. In addition, We also report an interaction effect between type of deviant and regularity that we did not expect. Omission of sounds were indeed detected before rare tones when they were presented regularly. This can be explained by the fact that, in absence a clear salient signal, participants could respond before they detected the actual occurrence of the omission based probably on an average estimate of their heart rate. Overall, our results support that participant rely on active inference strategies at the behavioral level since participants adapted their responses accordingly with regularity and deviant type, but that they did not rely on cardio-audio synchrony.

Nevertheless, we found total opposite patterns of effect on cardiac signals, suggesting that behavioral and cardiac responses to deviant are performed by two different mechanisms. Regarding cardiac signals, we managed to replicate the heart deceleration after omission when sounds were presented in synchrony found by Pelentritou et al. (2022) and Pfeiffer et De Lucia (2017). Our results furthermore show that this effect is also present when deviants are rare tones rather than omissions. Finally, unlike Pelentritou et al. (2022), we found that the cardio-audio synchrony effect resulted not only from a deceleration to the deviant when heart and sounds are synchronous, but also from an acceleration to the deviant when they are asynchronous. These results don't fit any of our model's predictions but correspond to a possibility that we did not anticipate and the last case of our conceptual space : an absence of effect of regularity and type of deviant. We, thus propose a novel hypothesis to accommodate for this finding, framing our effect as resulting from a startled surprise response.

In this model, cardiac activity would be modulated by deviant appearance according to cardio-audio synchrony due to an early automatic physiological response of surprise depending on a basic modification of input occurring independently of prediction processes and of the type of deviant (Skora, Livermore et Roelofs 2022. Such deceleration of cardiac responses are observed after threatening stimulus as a freezing response (Livermore et al. 2021) and has been interpreted throughout the literature as a way to reduce the internal noise associated with heartbeats to optimize external stimulus processing (Lacey 2007, Jennings et al. 1992, Skora, Livermore et Roelofs 2022,Roelofs 2017). This can be physiologically explained as resulting from the action of the parasympathetic system that cause cardiac deceleration, and its return to baseline by the removal of the parasympathetic brake and a sympathetically-driven cardiac acceleration (Roelofs 2017). On contrary, as asynchronous sounds would be not matching internal signals, deviations would be perceived as less threatening, and might even favor sympathetic system to promote action rather than sensory sampling. In this regard, the investigation of the other physiological signatures (EEG, EDA, respiration and pupil) might provide more information into how arousal systems are modulated after deviants in the synchronous and asynchronous conditions.

In line with Banellis et Cruse 2020, we found that participants could determine if sound sequences were synchronous or not with their heatbeat. Importantly, we also found that cardiac responses depended on interoceptive awareness abilities but not response types as we found an interaction between the synchrony effect and MAIA. Thus, our results show that cardio-audio synchrony is tightly related to interoception as measured by MAIA without relying on explicit awareness as measured by response types. Indeed, we found that these two interoceptive metrics were also uncorrelated. These results are in line with the fact that Pelentritou et al. (2022) found that cardiac deceleration to omission during synchronous sound sequences was preserved in all sleep stages, including deep NREM sleep when subjects are considered largely unconscious (Tononi et Massimini 2008). This finding further supports the hypothesis of an automatic cardiac startle response underlying the cardio-audio synchrony effect that might represent a preconscious marker of bodily connectedness with our environment largely unrelated to behavior. It would be thus interesting to test for the preservation of the cardio-audio synchrony as a marker of bodily connectedness in clinical settings where behavioral reports cannot be obtained such as under anesthesia, during altered states of consciousness or alongside post-comatose patients. As so, our findings is raising the question whether bodily connectedness and cardio-audio synchrony could be a way to assess covert interoceptive abilities and be used an early prognostic marker of consciousness recovery.

Several limits to these results deserve to be noted. First, our cardiac results are only preliminary as our physiological study remains under-powered with only 20 out of the 40 participants planned to be recruited. We thus need to acquire the second half of subjects for this experiment to be able to conclude on these results with an appropriate statistical power. Second, several participants described better sensing of cardiac rhythm in our lab settings under limited sensory stimulation. Moreover, we explicitly drew their attention on their interoceptive signals, allowing them to deploy explicitly strategies to determine whether sounds were synchronous or not with their heartbeats. Pelentritou et al. (2022) did not ask during the experiment about the synchrony of the sounds and a deceleration of cardiac rhythm after omission was found while participants reported post-hoc not having been aware of the presence of synchronous vs. asynchronous conditions, showing that this cardiac response do not depend on the explicit awareness of the cardio-audio synchrony. In agreement, we did not find an effect of response scores on our cardiac effect, but our task demands and particular laboratory context still potentially limit the ecological validity of our investigation of the cardio-audio effect. Further investigations could favour shorter sequences of sounds and enriched sensory contexts to limit strategic modulation of cardiac rhythm to determine synchrony condition and their attention to be overly focused on their internal signals.

6. Conclusion

As a conclusion, our results managed to replicate results from by Pelentritou et al. (2022) showing a cardiac deceleration to omission when the heart is synchronized to sounds. We further demonstrate that this effect extends to rare tones and that it is not modulated by predictability of the deviant. We also report a cardiac acceleration to deviants in the asynchronous condition. Importantly, we found that cardio-audio synchrony effects do not depend on the explicit awareness of the synchrony of sounds with the heartbeat, but on interoceptive abilities, suggesting an implicit interoceptive mechanism underlying extero-interoceptive integration during cardio-audio synchrony.

Since none of our a priori models could explain that neither regularity nor type of deviant influence such cardio-audio synchrony effect, we proposed an alternative hypothesis based on a startled surprise response. In this model, a deviant is considered threatening when occurring in synchrony with the heartbeat and triggers a cardiac deceleration to favor sensory sampling. On the contrary, deviants appearing asynchronously with the heartbeat would be considered less threatening and would promote an acceleration of heart rate to promote action. Nevertheless, at the behavioral scale, we found no influence of cardio-audio synchrony on response time to deviant detection but an effect of predictability and response type in line with the active inference model, suggesting that physiological and behavioral effects here depend on different mechanisms.

Our investigation of physiological effects reported here should however still be considered preliminary and need completion of data acquisition to be confirmed and of analysis of the other physiological signals to deepen our understanding of the phenomenon. In the future, we aim at investigating cardio-audio synchrony during altered states of consciousness such as anesthesia as cardio-audio synchrony might represent a potential covert maker of interoception and help to improve the assessment of sentience and consciousness levels in non-communicative states.

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Appendix

A. Data and code availability

All the data used in the main analyses are available for review and will be made publicly available upon publication. Custom-made code used to run both behavioral and physiological experiment, quality control analyses, behavioral, EEG and ECG data analyses are available on ”https ://gitlab.uliege.be/Kevin.Nguy/giga-crc-cardio-audio-expe”.

B. R peak to sound delays

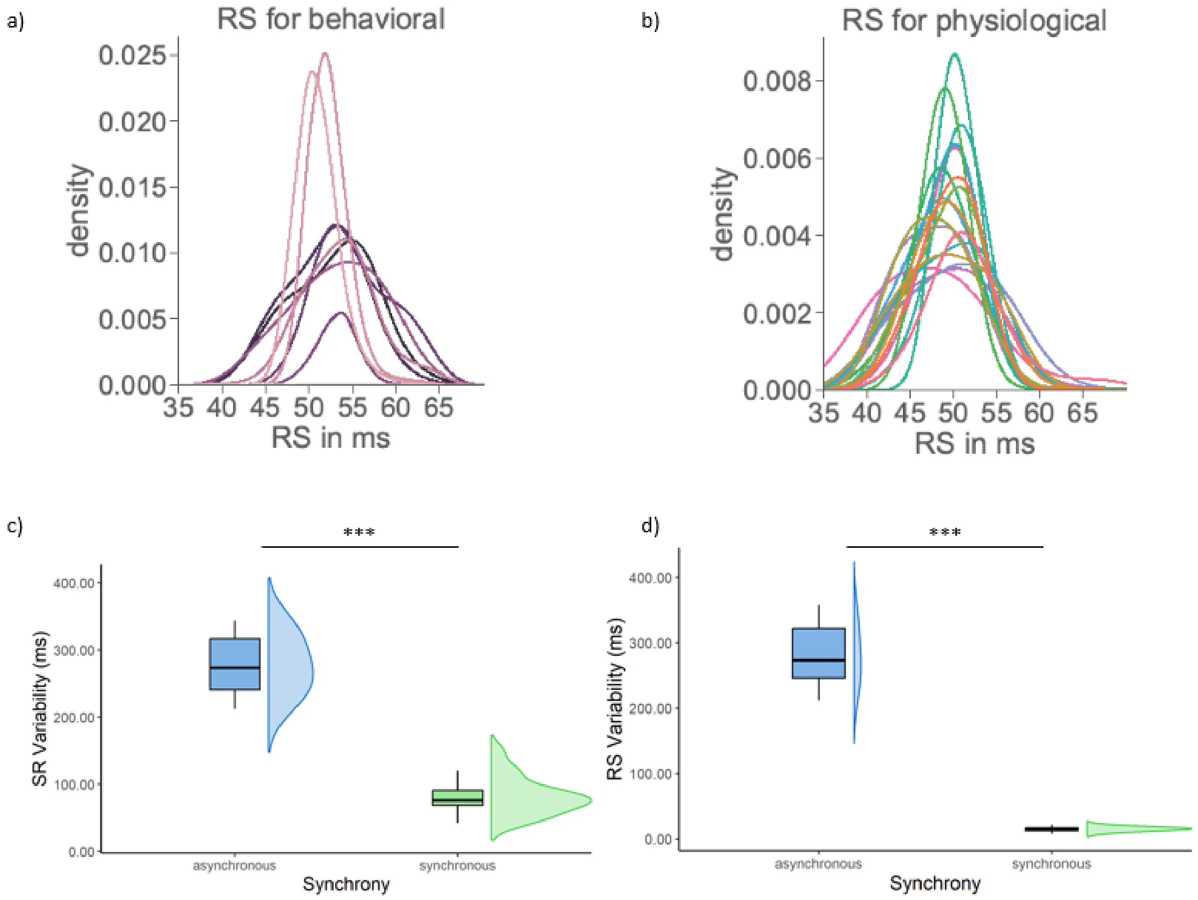


FIGURE 9 – *Performance of the closed loop stimulation procedure using the online detection algorithm to trigger Sound to generate the synchronous condition and the random shuffling of interbeat intervals of heartbeat intervals detected during baseline to generate the asynchronous condition. After extracting R-peak extracted offline, the R-peak to Sound density show that stimulus delivery is consistently locked to the R-peak across participants in the synchronous conditions in the behavioral* (*A*) *and physiological* (*B*) *experiments. R-peak to Sound onset* (*RS*) *variability* (*C*) *and Sound onset to R-peak* (*SR*) *variability* (*D*) *computed in the physiological experiment confirm the significant desynchronisation of sounds to heartbeats in the asynchronous condition as compared to its locking in the synchronous conditions. Post-hoc emmeans for significance testing* (*** : p<0.001)

C. Preliminary EEG figures

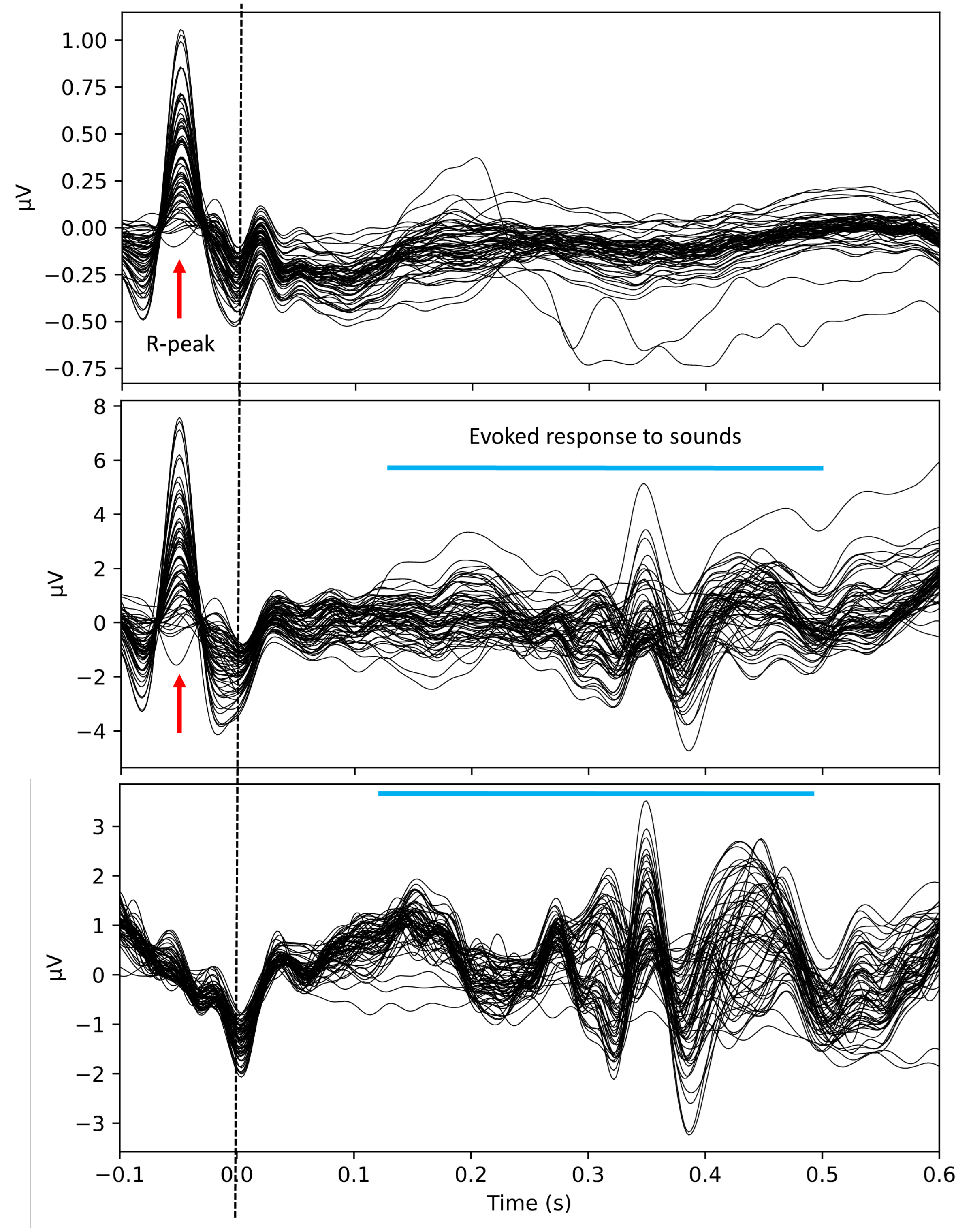


FIGURE 10 – *EEG responses locked to standard sounds onset for synchronous (middle-panel) and asynchronous (lower-panel) blocks and locked to the expected timing of sound onset if the detection algorithm is run during baseline trials (top-panel). Reponses for one representative subject were obtained after preprocessing by filtering between* 0.1 *and* 30 *Hz (FIR filter), notch-filtering at* 50 *Hz, and averaging across trials at each of the* 64 *EEG channels.*

D. FR-MAIA Questionnaire

Multidimensional Assessment of Interoceptive Awareness (MAIA) questionnaire (2012)

Évaluation multidimensionnelle de la conscience de soi

Vous trouverez ci-dessous une liste de propositions. Merci de bien vouloir indiquer la fréquence à laquelle chacune de ces propositions s'applique à vous, de façon générale, dans votre vie de tous les jours.

L'échelle de réponse va de 0 (pour "jamais") à 5 (pour "toujours")

1. Lorsque je suis tendu, je perçois où la tension se situe dans mon corps.
0 1 2 3 4 5

2. Lorsque je me sens mal dans mon corps, je le remarque.
0 1 2 3 4 5

3. J'identifie/je remarque à quel endroit de mon corps je me sens confortable.
0 1 2 3 4 5

4. Je perçois les changements dans ma respiration, par exemple lorsqu'elle ralentit ou accélère.
0 1 2 3 4 5

5. Je ne perçois pas (j'ignore) les tensions physiques ou l'inconfort jusqu'à ce qu'ils ne deviennent sévères.
0 1 2 3 4 5

6. Je me détache des sensations d'inconfort.
0 1 2 3 4 5

7. Lorsque je ressens de la douleur ou de l'inconfort, je m'efforce de les surmonter.
0 1 2 3 4 5

8. Lorsque je ressens une douleur physique, cela me stresse.
0 1 2 3 4 5

9. Je commence à me soucier que quelque chose n'aille pas dès que je ressens le moindre inconfort.
0 1 2 3 4 5

10. Je peux percevoir une sensation corporelle déplaisante sans m'en inquiéter.
0 1 2 3 4 5

11. Je peux prêter attention à ma respiration sans être distrait par les choses qui arrivent autour de moi.
0 1 2 3 4 5

12. Je peux rester conscient de mes sensations corporelles intérieures même lorsqu'il se passe beaucoup de choses autour de moi).
0 1 2 3 4 5

13. Lorsque je suis en conversation avec quelqu'un, je peux porter attention à ma posture.
0 1 2 3 4 5

14. Je peux rediriger mon attention sur mon corps si je suis distrait.
0 1 2 3 4 5

15. Je peux détourner mon attention de mes pensées pour la tourner vers mon corps (vers mes sensations corporelles).
0 1 2 3 4 5

16. Je peux conserver la conscience de l'ensemble de mon corps même lorsqu'une partie de moi-même éprouve de la douleur ou de l'inconfort.
0 1 2 3 4 5

17. Je suis capable de focaliser mes pensées de façon consciente sur mon corps dans son entier.
0 1 2 3 4 5

18. Je perçois comment mon corps change lorsque je suis en colère.
0 1 2 3 4 5

19. Lorsque quelque chose ne va pas dans ma vie, je peux le ressentir dans mon corps.
0 1 2 3 4 5

20. Je remarque que mes sensations corporelles changent après une expérience apaisante.
0 1 2 3 4 5

21. Je perçois que ma respiration devient dégagée et aisée lorsque je me sens confortable.
0 1 2 3 4 5

22. Je perçois comment mon corps change lorsque je me sens heureux/joyeux.
0 1 2 3 4 5

23. Lorsque je me sens débordé, je peux trouver un endroit calme à l'intérieur de moi.
0 1 2 3 4 5

24. Lorsque je prends conscience de mon corps, je ressens une sensation de calme.
0 1 2 3 4 5

25. Je peux utiliser ma respiration pour réduire la tension.
0 1 2 3 4 5

26. Lorsque je suis pris dans mes pensées, je peux calmer mon esprit en me concentrant sur mon corps / sur ma respiration.
0 1 2 3 4 5

27. Je suis à l'écoute de mon corps concernant mon état émotionnel.
0 1 2 3 4 5

28. Lorsque je suis stressé, je prends le temps d'explorer comment mon corps se sent.
0 1 2 3 4 5

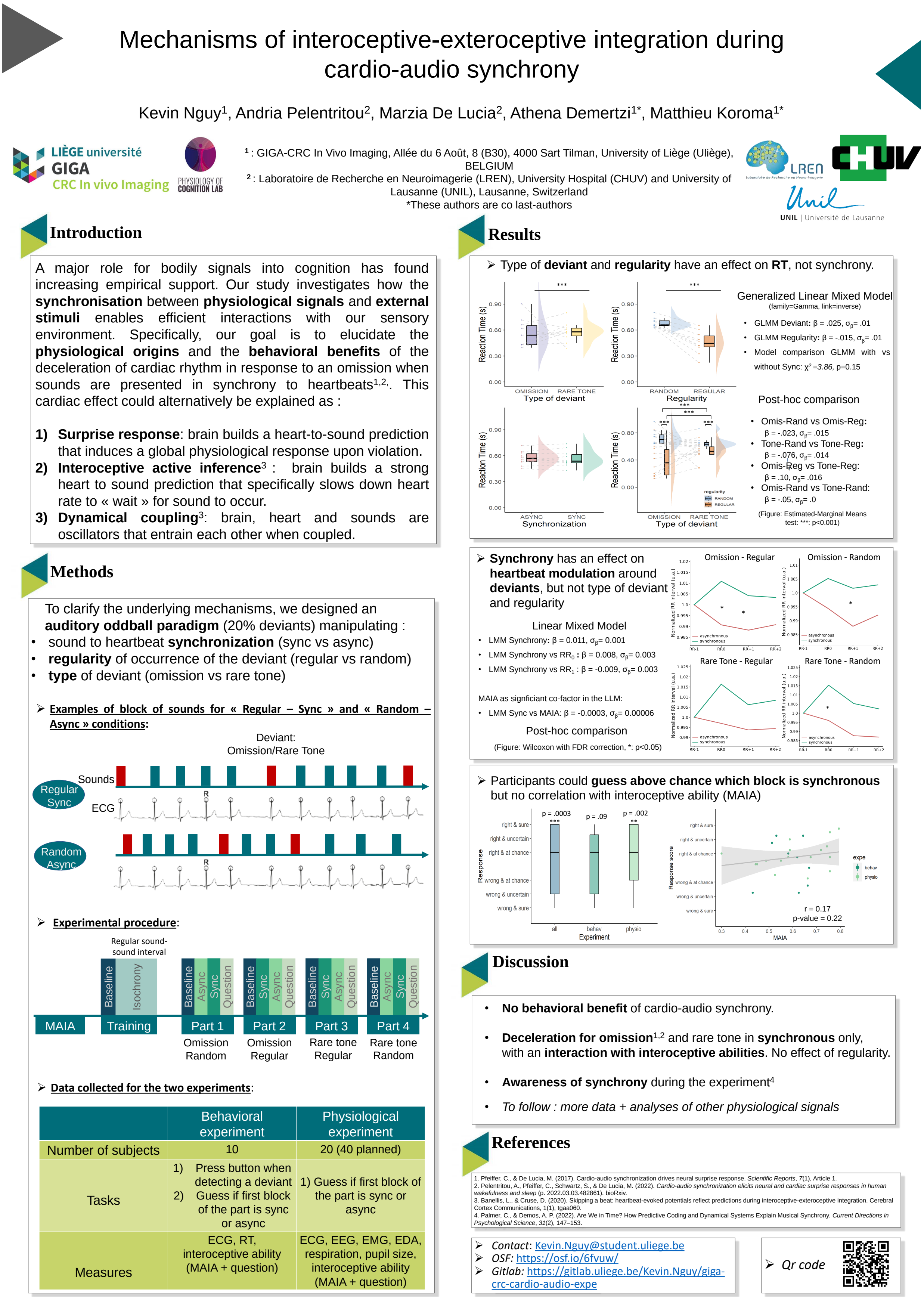
29. J'écoute mon corps afin de m'informer sur ce que je dois faire.
0 1 2 3 4 5

30. Je suis chez moi dans mon corps.
0 1 2 3 4 5

31. Je sens que mon corps est un endroit sûr.
0 1 2 3 4 5

32. Je fais confiance à mes sensations corporelles.
0 1 2 3 4 5

E. Poster made for the BAPS annual meeting (26th May 2023)



Mechanisms of interoceptive-exteroceptive integration during cardio-audio synchrony

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Introduction

A major role for bodily signals into cognition has found increasing empirical support. Our study investigates how the **synchronisation** between **physiological signals** and **external stimuli** enables efficient interactions with our sensory environment. Specifically, our goal is to elucidate the **physiological origins** and the **behavioral benefits** of the deceleration of cardiac rhythm in response to an omission when sounds are presented in synchrony to heartbeats[1,2]. This cardiac effect could alternatively be explained as :

1) **Surprise response**: brain builds a heart-to-sound prediction that induces a global physiological response upon violation.
2) **Interoceptive active inference**[3] : brain builds a strong heart to sound prediction that specifically slows down heart rate to « wait » for sound to occur.
3) **Dynamical coupling**[3]: brain, heart and sounds are oscillators that entrain each other when coupled.

Methods

To clarify the underlying mechanisms, we designed an **auditory oddball paradigm** (20% deviants) manipulating :

- sound to heartbeat **synchronization** (sync vs async)
- **regularity** of occurrence of the deviant (regular vs random)
- **type** of deviant (omission vs rare tone)

➢ **Examples of block of sounds for « Regular – Sync » and « Random – Async » conditions**:

➢ **Experimental procedure**:

➢ **Data collected for the two experiments**:

	Behavioral experiment	Physiological experiment
Number of subjects	10	20 (40 planned)
Tasks	1) Press button when detecting a deviant 2) Guess if first block of the part is sync or async	1) Guess if first block of the part is sync or async
Measures	ECG, RT, interoceptive ability (MAIA + question)	ECG, EEG, EMG, EDA, respiration, pupil size, interoceptive ability (MAIA + question)

Results

➢ Type of **deviant** and **regularity** have an effect on **RT**, not synchrony.

Generalized Linear Mixed Model
(family=Gamma, link=inverse)

- GLMM Deviant: $\beta = .025$, $\sigma_\beta = .01$
- GLMM Regularity: $\beta = -.015$, $\sigma_\beta = .01$
- Model comparison GLMM with vs without Sync: $\chi^2 = 3.86$, p=0.15

Post-hoc comparison

- Omis-Rand vs Omis-Reg: $\beta = -.023$, $\sigma_\beta = .015$
- Tone-Rand vs Tone-Reg: $\beta = -.076$, $\sigma_\beta = .014$
- Omis-Reg vs Tone-Reg: $\beta = .10$, $\sigma_\beta = .016$
- Omis-Rand vs Tone-Rand: $\beta = -.05$, $\sigma_\beta = .0$

(Figure: Estimated-Marginal Means test: ***: $p<0.001$)

➢ **Synchrony** has an effect on **heartbeat modulation** around **deviants**, but not type of deviant and regularity

Linear Mixed Model

- LMM Synchrony: $\beta = 0.011$, $\sigma_\beta = 0.001$
- LMM Synchrony vs RR_0 : $\beta = 0.008$, $\sigma_\beta = 0.003$
- LMM Synchrony vs RR_1 : $\beta = -0.009$, $\sigma_\beta = 0.003$

MAIA as signficiant co-factor in the LLM:

- LMM Sync vs MAIA: $\beta = -0.0003$, $\sigma_\beta = 0.00006$

Post-hoc comparison

(Figure: Wilcoxon with FDR correction, *: $p<0.05$)

➢ Participants could **guess above chance which block is synchronous** but no correlation with interoceptive ability (MAIA)

Discussion

- **No behavioral benefit** of cardio-audio synchrony.
- **Deceleration for omission**[1,2] and rare tone in **synchronous** only, with an **interaction with interoceptive abilities**. No effect of regularity.
- **Awareness of synchrony** during the experiment[4]
- *To follow : more data + analyses of other physiological signals*

References

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4. Palmer, C., & Demos, A. P. (2022). Are We in Time? How Predictive Coding and Dynamical Systems Explain Musical Synchrony. *Current Directions in Psychological Science*, *31*(2), 147–153.

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➢ *Qr code*

Figure 11 – *Poster presented on the occasion of the Belgian Association for Psychological Sciences annual meeting - 26th May 2023 at Mons, Belgium*

F. AMU convention anti-plagiat

CHARTE RELATIVE A LA LUTTE CONTRE LE PLAGIAT DE L'UNIVERSITE D'AIX-MARSEILLE

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