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**The heart to make the right choice: Vagal (re)activity and recovery predict
advantageous decision-making**

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Abstract (max 250 words):

From simple everyday choices to life-altering decisions, decision-making is a crucial cognitive process in our daily life. Psychophysiological theories of heart-brain interactions involvement in cognition predict that general self-regulation capacities underlie cognitive processes including decision-making. Yet, in the context of decision-making, the somatic marker hypothesis postulates that the adaptability of the current physiological state should be the best predictor of advantageous decision-making. The present study tests compare self-regulation in general (indexed by resting vagal activity) and in a specific decisional context (vagal reactivity and recovery) to explain advantageous decision-making. Young adults ($n = 54$) completed a decision-making task while wearing a heart rate monitor. Bayesian regressions show that vagal reactivity and recovery combined is the preferred statistical model to explain advantageous decision-making ($BF_{10} = 163.85$). Those findings 1) support the somatic marker hypothesis highlighting the key role of in situ self-regulation in decision-making processes and 2) show that the popular and often used index of general self-regulation, resting vagal activity, is not the best predictor of decision-making performance, and perhaps even for other cognitive functions. A next step could be interventional studies to test whether vagal modulation of heart rate underlies decision-making through interventions that influence vagal activity, which could provide relevant clinical leads.

Keywords: Heart rate variability, embodied brain, somatic marker, vagal tone, rationality

Introduction

Decision-making is essential in daily life, as such, many studies have explored its determinants [1–3]. Among them, bodily signals (e.g., interoceptive afferent, autonomic activity) are now recognized to play an important role [4,5]. According to the somatic marker hypothesis [5], the cognitive system relies on the physiological state provoked by the consequences of previous decisions. Decisions resulting in favorable outcomes should be associated with positive emotions and thus increase the likelihood to make the same decision in a similar situation, while the reverse should occur for negative outcomes. Physiological reactions are thought to be at the origin of emotion, and thus of associated cognition according to the historical James-Lange [6] and more recent two-factors [7,8] models of emotion. The cerebral integration of physiological signals resulting from a decision is underpinned by the insular cortex and then processed by other cortical areas, especially the prefrontal regions [9]. According to the neurovisceral integration model [10], both the insular cortex and the prefrontal regions are part of the central autonomic network. These regions are recognized to underpin the executive functions [11,12] which are crucial to decision-making [13,14].

The vagus nerve is considered as the primary factor mediating the relationship between physiological state and central autonomic network activity [10] through the integration of vagal activity by the insular cortex [15]. Therefore, vagal modulation of the heart at rest (i.e. resting vagal activity) is a popular and frequently used index of general self-regulation closely related to executive functioning [10]. Accordingly, resting vagal activity (measured by heart rate variability) has been consistently and positively associated with performance in a range of tasks measuring executive functioning performance [16] and decision-making [17]. Yet, in the context of decision-making, the nature of the decision made is highly influenced

by the context in which it takes place [3]. In the same way, recent models on vagal activity defend a dynamic approach in which vagal activity represents a better index of cognitive's related self-regulation index when it is measured in situ (vagal modulations) rather than in general (resting vagal activity) [18]. Consequently, decision-making should more rely on the dynamic vagal activity rather than the general level of vagal activity. The present study, therefore, seeks to investigate whether vagal modulations during a specific decision-making task (in situ self-regulation) better predict decision-making than resting vagal activity (general self-regulation), which has never been tested previously.

This hypothesis is predicted by the vagal tank theory which postulates that, rather than resting vagal activity, vagal activity changes during and after a task are essential to reflect in situ self-regulation at a given time and in a specific context [18]. Self-regulation at a given time would thus mainly rely on cardiac vagal control, i.e. the ability of the vagus nerve to alter heart rate with high responsiveness, precision, and sensitivity which can be assessed by considering vagal reactivity to and recovery from a specific task [19]. Those indexes represent different levels of adaptability: while reactivity is crucial to cope with the task's demands [20], recovery reflects the return to the resting state before facing another event, such as another decisional context [21]. Accordingly, earlier research has suggested that vagal modulation during a task may better predict cognitive performance than vagal activity at rest [22]. In the context of decision-making, it was recently reported that a higher vagal modulation during a decision-making task seems to occur in good decision-makers [23]. Going a step further, the present study aims to compare self-regulation as a general ability (vagal activity at rest) or in a specific context (vagal reactivity and recovery) to explain advantageous decision-making using a Bayesian approach. The advantage of Bayesian statistics is to allow testing of any combination of the variables of interest (resting vagal

activity, reactivity, and recovery) in statistical submodels to verify which combination has the highest degree of fit with respect to the hypothesis being tested (in this case, explaining advantageous decision-making) [24,25]. More precisely, this statistical approach tests how much one model is preferable to others instead of testing whether a model is significantly different from another [26]. We expected that combined vagal reactivity and recovery should explain advantageous decision-making in a greater way than resting vagal activity alone. Higher reactivity and vagal recovery should predict a higher rate of decisions with a favorable outcome in a decision-making task.

Method

Participants

A priori, the sample size was determined by using the “*pwr*” package in R [27] with the parameters found in a study testing vagal activity as a predictor of decision-making [17] from which an effect size of Cohen’s $f^2 = .20$ was computed. With .80 power, the analysis revealed a sample size of 55 participants. Due to the possible exclusion of some participants (see below) and to ensure sufficient statistical power, sixty-six undergraduate psychology students were enrolled.

Inclusion and exclusion criteria were controlled through an interview on their sociodemographic data (age, sex, etc.) and medical histories. Conditions that may affect cognition and cardiovascular functioning, such as neurological (head trauma, epilepsy, etc.), physiological (hypo- or hyperthyroidism, type 2 diabetes...), or neurodevelopmental (autism, dyslexia...) conditions were defined as exclusion criteria. Similarly, lifestyle habits likely to affect the autonomic nervous system and cognitive functioning were screened as well, such as binge drinking alcohol (> 5 consecutive alcoholic drinks in the last week), high body mass index ($BMI \geq 30$), and smoking. Depression and anxiety were also controlled by the Hospital

and Anxiety Depression Scale [HADS, see 28]. Based on those criteria, 2 participants were excluded: 1 suffered from depression and 1 suffered from a heart condition. Another participant was excluded after starting the decision-making task without fully reading and understanding the instructions. After the removal of 9 outliers due to statistical constraints (see Statistical Analyses section), the final sample thus consisted of 54 participants ($M_{Age}=19.59$, $SD_{Age}=2.04$, 5 men). The research was approved by the Île-de-France Ethics Committee (2021-A01735-36).

Material

Vagal activity, reactivity, and recovery assessment

The heart rate variability measurements were carried out in accordance with the approved recommended guidelines in psychophysiological research [19,29–31]. The Polar H10 heart rate monitor provided electrocardiogram and inter-beat interval recordings. The accuracy and sensibility of this chest strap are validated for low and high-intensity activities, and this heart rate monitor is considered as the gold standard of wearable devices for heart rate assessment [32]. Heart rate was recorded during the whole 45 minutes experimental session. Triggers, applied via the Polar Sensor Logger smartphone app (version 3.0.0), were used to delineate the sections of the recording used to extract inter-beat intervals. More precisely, after 5 minutes of resting time, inter-beat intervals were extracted from the 5 minutes baseline right before the decision-making task, the 5 minutes during the task, and the 5 minutes following the task [as recommended, see 18,33]. A visual check ensured the quality of the recordings as the control of artifacts or occasional ectopic. Furthermore, the premium version of Kubios (v.3.5.0) automatically applies a low threshold filter in case noise is detected. High Frequency (HF, ranging from 0.15 to 0.4 Hz) power, a widely used and reliable index of vagal activity [19,34] that is the percentage of HF among the total power minus the very low

frequency (normal units) was computed [35]. The vagal reactivity was obtained by computing the difference between resting HF power and HF power during the task while vagal recovery was obtained from the difference between HF power during and following the task [18].

Decision-making assessment

A computerized version of the Iowa Gambling Task [IGT, see 13] was adapted for the original version of this task [see also 36, for a HRV study]. In this task, 4 decks of cards are displayed on the screen (see Figure 1). All participants start with a virtual €2,000 credit. The participants must choose one card at a time and can change decks at any time. With each selection, virtual money is won and, sometimes, lost. The amount of money won or lost depends on the deck selected. Decks 1 and 2 always pay €100 and 3 and 4 always pay €50. Decks 1 and 2 pay more, but also lead to higher losses. There is a 1 in 10 chance of losing €1,250 in Deck 1, while for Deck 2 there is a 1 in 2 chance of losing a sum ranging from €150 to €350. On 10 trials the total loss for Decks 1 and 2 amounts to €1,250. In deck 3, there is a 1 in 10 chance of losing €50 while in deck 4, there is a 1 in 10 chance of losing €250. In order to select the cards, the participants used the mouse, which returns to the center of the screen after each selection. The test ended automatically after the individual made the 100th selection, a rule of which participants were unaware of. The participants were informed that some decks were more advantageous than others. A rationality score was computed based on the number of times a disadvantageous deck (Deck 1 and 2) was selected divided by the number of advantageous choices (Deck 3 and 4) as recommended in the literature [13].

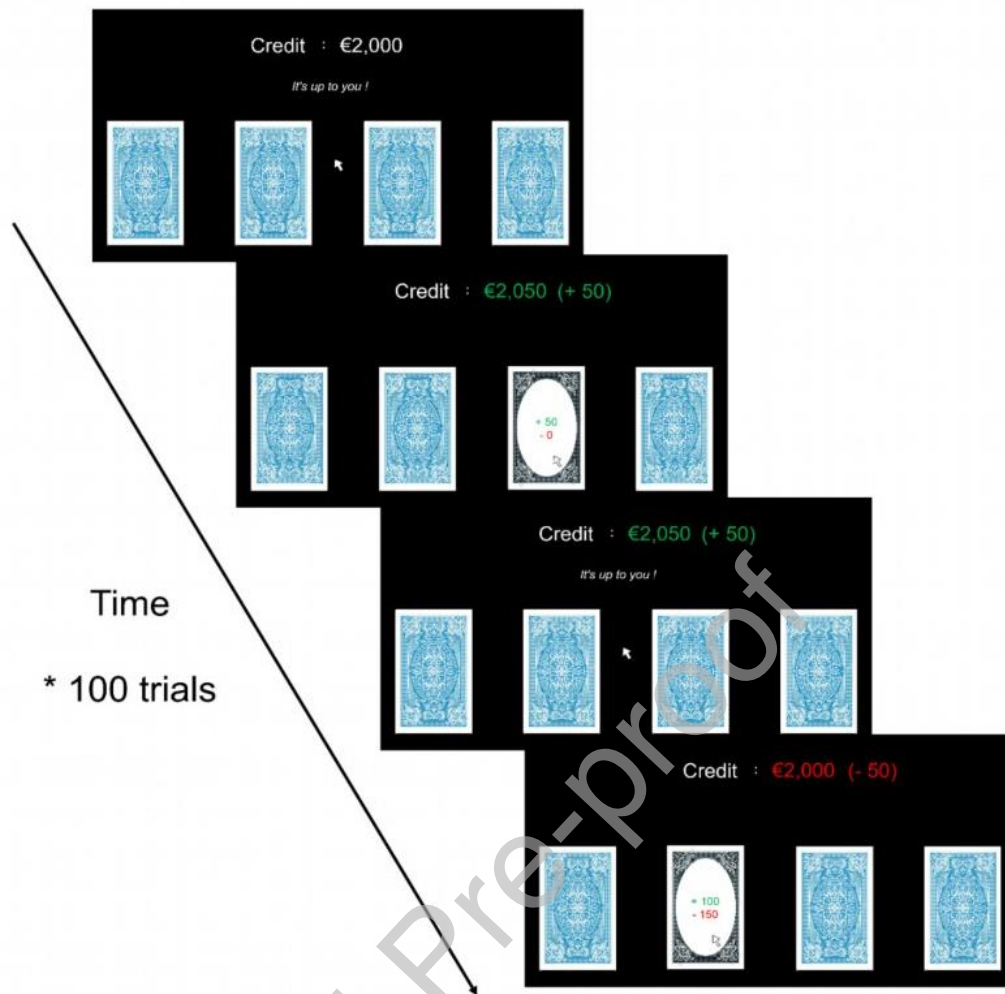


Figure 1. Illustration of the computerized version of Iowa Gambling Task (IGT).

Procedure

This study was part of a larger project also testing the association between HRV and visual perception. Some administered tests were thus not considered in this study. Each participant was tested individually in a session that lasted approximately 45 minutes. After consent, the experimenter gave instructions so that participants could install the Polar H10 heart rate monitor by themselves. To ensure recording quality after the installation of the chest strap, a smartphone application (Polar Sensor Logger) displaying the ECG recording in real time was used. During a 10-minute rest period, health and sociodemographic data were collected. Then, participants completed the heartbeat counting task (i.e. asking participants to count

their perceived heartbeats without taking their pulse to measure cardioception [37]) followed by 5 minutes of resting time before the IGT. After 5 minutes of rest to ensure HRV recovery [18], a visual perception task was administered (lasting 10 minutes). This computerized task assessed the angle estimation of displayed geographical slants. The session ended with three questionnaires, the interoceptive awareness questionnaire [38], the emotion regulation questionnaire [39], and HADS [28]. Finally, a debriefing was proposed to present the hypotheses of the study, answer any questions as well as collect participants' feedback on the task.

Statistical analyses

All the statistical analyses were performed in the R statistical environment, version 4.0.2 [40]. To test whether vagal reactivity and recovery predict greater beneficial decision-making than its resting state, frequentist regression analyses were performed. Then the same analyses were conducted in Bayesian to compare all the possible sub-models in relation to H1. First, the assumptions (multi-collinearity, homoscedasticity, independence of errors...) were checked using the package "car" [41] for all variables of interest. Outliers detection using absolute deviation around the median [42] revealed 9 participants with extreme decision-making results which were excluded from further analyses as recommended [see 43]. All the assumptions were met after the removal of outliers identified by the median absolute deviation diagnostic [42]. Then frequentist multiple regression analysis was computed with resting HF, HF reactivity, and HF recovery as predictors and the rationality ratio as the dependent variable. To go further, the same model was conducted with a Bayesian approach using the BayesFactor R package [44] to test whether a submodel including HF reactivity and recovery is preferred over other possible models. Bayes factors were computed as the ratio of the likelihood of one particular hypothesis (H1) to the likelihood of another (H₀). A Bayes

factor BF_{10} of 1-3, 3-10, 10-30, 30-100, > 100 can be respectively interpreted as anecdotal, moderate, strong, very strong, and extreme evidence for the alternative H_1 relative to the null hypothesis H_0 [45–47]. We have tested sex ratio and age as potential covariables. As the results were highly similar to the model without covariables, we decided to report here a regression model with only the variables of interest to keep the message as clear as possible.

Results

A multiple linear regression model ($F(3, 50) = 6.84, p < .001, R^2 = .25$) show that HF reactivity ($\beta = .017, p = .002$) and HF recovery ($\beta = .012, p = .02$) positively predict the rationality score while HF rest is not a significant predictor ($\beta = -.002, p > .10$). Testing the different sub-models (see Figure 2), the Bayesian multiple regression analysis revealed anecdotal evidence for HF recovery ($BF_{10} = .28$), resting HF combined with HF reactivity ($BF_{10} = 2.44$), moderate evidence for HF reactivity ($BF_{10} = 5.75$) and resting HF ($BF_{10} = 6.68$), strong evidence for resting HF and HF reactivity combined ($BF_{10} = 16.75$), very strong evidence for resting HF, HF reactivity and recovery all three added ($BF_{10} = 54.36$) and extreme evidence for HF reactivity and recovery combined ($BF_{10} = 163.85$) in relation with the rationality ratio. As expected, the Bayesian model with HF recovery and HF reactivity combined is preferred than the Bayesian model with the three predictors, resting, reactivity and recovery of HF (models' comparison: $BF_{10} = 3.01$) and other possible models (see Figure 2).

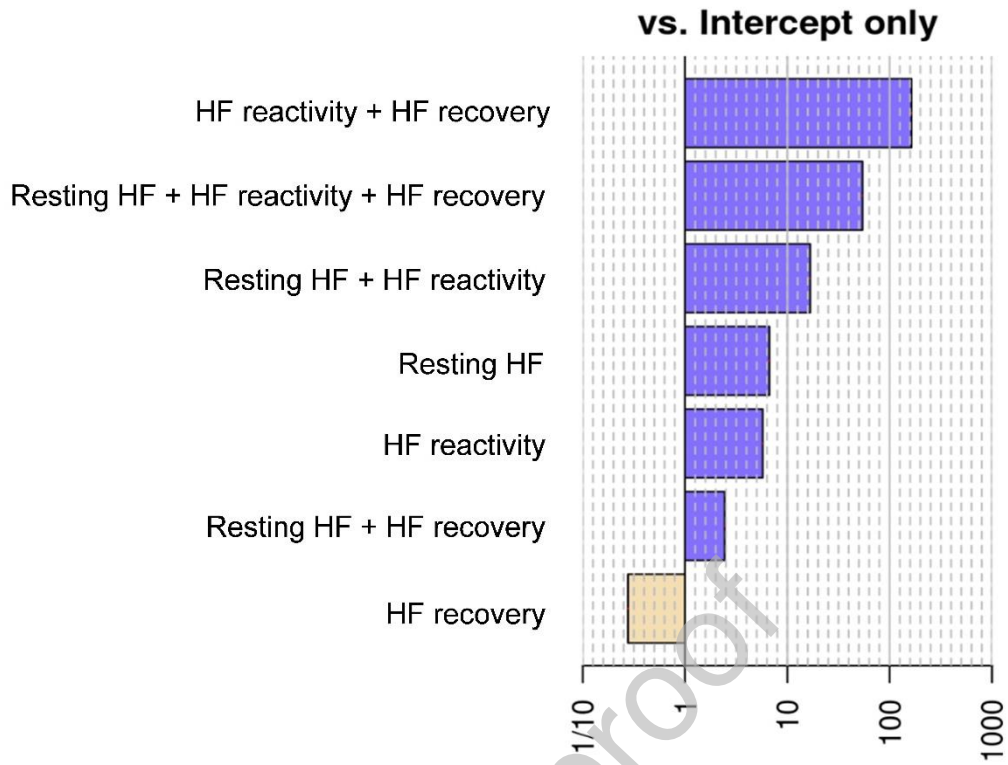


Figure 2. Resting HF, reactivity, and recovery in relation to decision-making with Bayes factor in the horizontal axis and different Bayesian models tested in the vertical axis.

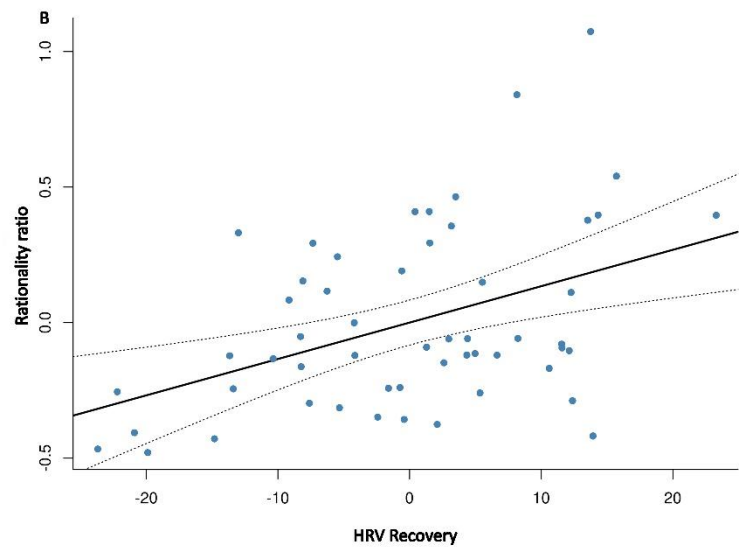
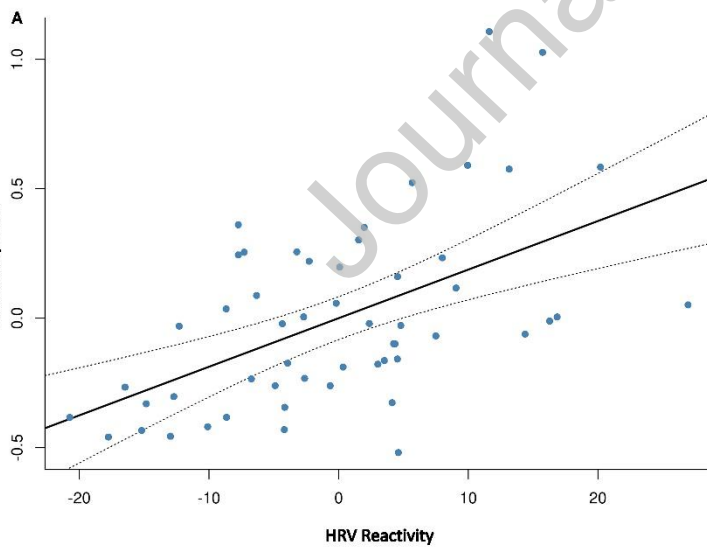


Figure 3. Added variable regression plots based on the preferred model (HF reactivity + HF recovery) representing the relation between HF reactivity and rationality score (A) and HF recovery and rationality score (B).

Discussion

Heart-brain interactions mediated by the vagus nerve predict that self-regulation, classically indexed by vagal activity at rest, is associated with complex cognitive processes such as executive functioning and decision-making [10,17,48]. In contrast, according to the somatic marker hypothesis [5], advantageous decision-making would be best explained by physiological adaptability during the decisional context (indexed by vagal reactivity and recovery, see [18]). Therefore, this study aims at comparing self-regulation in general (indexed by resting vagal activity) and self-regulation in situ (indexed by vagal reactivity and recovery) to explain advantageous decision-making. Using a Bayesian approach, in the present study, we show for the first time that vagal reactivity and recovery combined predict advantageous decision-making in a greater way than resting vagal activity alone or all other combinations.

These results are consistent with previous findings suggesting that only individuals performing well in a decision-making task exhibit acute vagal modulation during the task [23]. By going a step further, our findings suggest that specifically higher vagal reactivity and recovery from a decision-making task predict more advantageous decisions taken during the task, which is compatible with the somatic marker hypothesis [4,5]. While resting vagal activity is often the main index of self-regulation used in relation to cognitive performance [48–50], it is relevant to reflect solely general self-regulation abilities [10] which might not be appropriate to index the involvement of the autonomic nervous system in cognitive

performance in a specific context. Our findings confirm that the resting vagal activity positively predicts advantageous decision-making. Yet, a model with resting vagal activity in addition to reactivity and recovery is less predictive of advantageous decision-making than a model with only vagal reactivity and recovery. The best predictor of advantageous decision-making might thus be *in situ* physiological adaptability (vagal reactivity and recovery) rather than in general (resting). Supporting this hypothesis, it was suggested for other cognitive tasks (measuring cognitive inhibition) that vagal activity changes during the task were better predictors of cognitive performance than vagal activity at rest [22]. The activity of the autonomic nervous system can be considered as one of the main sources of somatic markers that can generate influence mental operations through the vagus nerve and thus underpinning to some extent decision-making processes [9].

Taken together, those results support recent advances in cognitive neuroscience on the role of heart-brain interactions in cognition [10,51,52]. Resting vagal activity represents a popular marker of self-regulation associated with performance on several cognitive tasks [48,16]. Yet, the present study shows that the reactivity to, and recovery from, a decision-making task might be key to advantageous decision-making highlighting the relevance to consider real-time changes in vagal activity during a specific context to index self-regulation [18]. Nonetheless, the current study presents some limitations. Despite controlling for many possible cofounders and the most likely to influence immediate HRV measurements (such as BMI, alcohol, medication, psychopathology, and medical condition [19]), several variables that could influence cardiac activity or cognitive performance were not taken into account. Among them, physical activity level [53], meditation practice [54], and sedentariness [55,56] were not controlled. In addition, even though smoking was collected and served as relevant

information for potential exclusion, it was not statistically controlled and the sex ratio was unbalanced (although it was not associated with any of the variables of interest).

This study raises important possible clinical implications. Accumulating evidence shows that a simple short breathing exercise can enhance vagal activity [57,58]. If the vagal reactivity and recovery underpin advantageous decision-making rather than resting vagal activity, such exercises before a difficult decision may increase the probability of making a choice to lead to favorable consequences. Another application would be transcutaneous auricular vagus nerve stimulation that can modulate vagal activity in a non-invasive way [59,for opposing results, see 60]. Future studies could investigate if both of these clinical applications stimulate the activity and enhance the adaptability of the vagus nerve resulting in more advantageous decision-making.

Authors' contributions

Conceived and designed the experiments: V.M., G.T.V. Performed the experiments: V.M.
Analyzed the data: V.M., G.T.V. Providing feedback: F.D. Prepared first manuscript draft:
V.M. All authors reviewed the manuscript.

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Declaration of interest

None

Ethics approval

The research was approved by the Île-de-France Ethics Committee (2021-A01735-36).

Data availability statement

The data used in the present study can be found at: <https://osf.io/kqgm9>

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