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Credit Author Statement

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Does heart rate variability predict better executive functioning? A systematic review and meta-analysis

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1 Abstract

2 The recent focus on the bidirectional heart-brain interactions in psychoneurophysiological research
3 has led to a variety of findings suggesting vagal activity is associated with cognition and, possibly,
4 specifically with executive functioning. This systematic review and meta-analysis aimed to provide
5 a better understanding of the association between vagally-mediated heart rate variability (HRV)
6 and executive functioning. We included 13 correlational studies. We found a small positive
7 association between vagally-mediated HRV and executive functioning ($r = 0.19$, 95%CI 0.15 to
8 0.23, $p < 0.0001$) using a quantitative synthesis of existing studies with random-effect models.
9 Conducting meta-regression analyses, we found that vagally-mediated HRV predicts cognitive
10 inhibition and cognitive flexibility more than working memory. In addition to the specific executive
11 function measured, this relationship is moderated by the HRV measurement used, and age. After
12 proposing a theoretical interpretation of the results, we emphasized the need for further research in
13 light of the methodological issues identified in the included studies, and we outline several aspects
14 to consider in future studies.

15

16 **Keywords:** Autonomic nervous system, vagal tone, cognition, psychophysiology, embodied brain

17

18 **Introduction**

19 Advances in cognitive neuroscience and psychophysiology on body-brain interactions (Bruineberg
20 & Rietveld, 2014; Kiverstein & Miller, 2015; Pezzulo & Cisek, 2016) has increasingly confirmed
21 the role of bodily signals in mental processes (Badcock et al., 2019; Damasio & Carvalho, 2013;
22 Seth, 2013). Accordingly, several peripheral factors, such as enteric microbiota (Cryan & Dinan,
23 2012), muscle mass (Pedersen, 2019), and the secretion of certain hormones (e.g., the link between
24 adrenal hormones and memory (McGaugh, 2013)), seem to influence cognitive processes. Recent
25 work on body-brain interactions has focused on the role of visceral signals and autonomic activity
26 in changing cerebral dynamics and cognition (Azzalini et al., 2019). Indeed, as cognitive
27 functioning worsens under conditions of autonomic dysfunctions, a promising physiological
28 correlate of cognitive functioning is thus the autonomic nervous system functioning (Forte et al.,
29 2019; Porges, 2007; Thayer et al., 2009). The autonomic nervous system is composed of the
30 sympathetic nervous system (mainly associated with physiological “flight or fight” responses) and
31 parasympathetic nervous system (depending on vagal activity, mainly related to energy
32 conservation, rest, and relaxation (Wehrwein et al., 2016)) which are associated with neural
33 dynamics (Sattin et al., 2020).

34 Bidirectional interactions between the autonomic and central nervous systems, primarily mediated
35 by the vagus nerve, are predicted by the neurovisceral integration model (Thayer et al., 2009).
36 According to this model, the functioning of the autonomic nervous system is an index of an
37 organism's self-regulatory capacities, promoting flexibility and adaptability in a changing
38 environment (Thayer & Lane, 2000). The primary marker of self-regulation is the vagal inhibition
39 of the heart, which can be assessed by recording the naturally occurring fluctuation in time intervals
40 between succeeding heartbeats over time, called heart rate variability (HRV, see Shaffer &

41 Ginsberg, 2017). Although heart-brain interaction can be measured by several methodologies such
42 as electrocardiogram heartbeat-evoked potentials (i.e., neural responses to heartbeats, see H.-D.
43 Park & Blanke, 2019) and psychological correlates of the phases of the cardiac cycle (Skora et al.,
44 2022), HRV is a non-invasive index of cardiac control (Shaffer et al., 2014) widely adopted in
45 psychophysiological research (Quintana & Heathers, 2014). Frequently used HRV measurements
46 include the high-frequency band (HF) of the HRV power spectrum which coincides with
47 respiration (typically 0.15 to 0.4 Hz, called the respiratory band), the root mean of the square
48 successive differences (RMSSD), and respiratory sinus arrhythmia (RSA) which are associated
49 with vagal activity (McCraty & Shaffer, 2015). While HF is a marker of parasympathetic activity
50 (Shaffer & Ginsberg, 2017), lower frequencies (LF, 0.04 to 0.15 Hz) have been considered as a
51 marker of sympathetic activity, but not exclusively (as it seems to be also influenced by
52 parasympathetic activity, see Hayano & Yuda, 2019). The LF/HF ratio would thus reflect the
53 autonomic balance resulting from the hypothesis that the sympathetic and parasympathetic nervous
54 systems competitively regulate sinoatrial node firing (Billman, 2013). However, it is now generally
55 accepted that both branches of the autonomic nervous system can be simultaneously active
56 (Berntson & Cacioppo, 1999) making LF/HF ratio interpretation controversial (Billman, 2013;
57 Hayano & Yuda, 2019). Overall, vagally-mediated HRV is considered as the most relevant index
58 of self-regulatory abilities (Thayer et al., 2012).

59 Indeed, vagally-mediated resting-state HRV is associated with activity in several neural networks,
60 including brain areas involved in emotion processing (e.g., amygdala), visceral integration (e.g.,
61 insular cortex), attentional and memory processes (e.g., prefrontal cortex, see Thayer et al., 2009).
62 For example, with respect to emotional processing, recent evidence shows that autonomic activity
63 may play a causal role in emotional responses, in which afferent signals from vagal activity precede
64 neural dynamics and correlate with the reported level of arousal (Candia-Rivera et al., 2022), and

65 may also be involved in emotional regulation through bodily feedback (e.g., in mice, see Klein et
66 al., 2021). Other recent studies suggested a role of cardiac activity in ventromedial prefrontal
67 activity influencing decision-making (Azzalini et al., 2021) and in measures of agency (the
68 experience of control and causing desired effects in the environment, see Herman & Tsakiris,
69 2020). Also, the cardiac cycle seems to be associated with the timing of action (Palser et al., 2021)
70 and the active processing of visual information (Kunzendorf et al., 2019). Together, these results
71 suggest that autonomic activity may have an ascending influence on brain, and thus cognitive,
72 processes. In line with this hypothesis, vagally-mediated resting-state HRV has been associated
73 with better performance on tasks assessing, for instance, emotion recognition (Quintana et al.,
74 2012), heartbeat detection (Lischke et al., 2021), cognitive flexibility (Colzato et al., 2018),
75 cognitive inhibition (Ottaviani et al., 2019), working memory (Laborde et al., 2015), memory
76 retrieval (Gillie et al., 2014), memory discrimination (Feeling et al., 2021). A recent systematic
77 review further supports the association between HRV and cognitive functioning, highlighting that
78 vagally-mediated resting-state HRV seems to be specifically associated with executive functioning
79 (Forte et al., 2019).

80 Although HRV has been associated with several cognitive functions (e.g., memory and attention,
81 see Forte et al., 2019), it is rather considered as a marker of executive functions that may be
82 involved in other cognitive functions (such as the involvement of executive functions in memory,
83 see Feeling et al., 2021). Executive functioning can be defined as the control processes
84 implemented when the usual courses of action are no longer relevant in a given context (i.e., new,
85 unfamiliar, dangerous, or conflicting situations) allowing the person to adapt to new situations
86 (Diamond, 2013). According to Miyake's framework, the three main components of executive
87 functioning are task-switching, updating working memory, and response inhibition, playing a
88 crucial role in complex cognition and regulatory processes (Hsu et al., 2014; Miyake et al., 2000).

89 Executive functioning, being relatively malleable (Hsu et al., 2014), could be influenced by vagal
90 activity, as vagally-mediated HRV is a marker of self-regulatory abilities (Thayer et al., 2012). Yet,
91 the magnitude, robustness, and mechanisms involved in the association between HRV and
92 executive functioning remain unclear. For instance, several methodological issues have been
93 identified to explain the inconsistency of the results such as the lack of control for sexual
94 dimorphism (likely to influence autonomic responses, see Koenig & Thayer, 2016), the high
95 variability of the data attributable to different methodological procedures and study designs, and
96 executive functions have not previously been assessed in detail (Forte et al., 2019). Moreover,
97 inhibition is considered as a common executive factor, underlying the performance in all executive
98 function tasks (Miyake & Friedman, 2012). As the neuro-integration visceral model (Thayer et al.,
99 2009) predict that HRV is associated with executive functioning, if cognitive inhibition is the core
100 component of executive functions (Miyake & Friedman, 2012), then HRV might be more strongly
101 associated with some executive component rather than others. In the same way, some HRV
102 measurements have been described to reflect not only vagal activity but also sympathetic activity
103 (Berntson et al., 2005). If vagal activity is associated with executive functioning, then the HRV
104 measurements reflecting both vagal and sympathetic activity should be less predictive of executive
105 functioning than other vagally-mediated HRV measurements.

106 In the present study, we aimed to investigate this association in a systematic review and meta-
107 analysis in order to contribute to a better understanding of how HRV might be related to executive
108 functioning. The primary objective of this study was to synthesize studies in which the relationship
109 between vagally-mediated HRV and executive functioning has been tested and to assess the
110 magnitude of this relationship by addressing the methodological issues previously identified
111 (control of sexual dimorphism, heterogeneity in study design and population studied etc., see
112 Forte et al., 2019). Secondary objectives included (1) testing whether a specific measurement of

113 vagally mediated HRV better predicted executive functioning than others, (2) testing whether a
114 specific executive function was predicted more by vagally-mediated HRV than the others, (3) and
115 determining possible moderators of this association such as sexual dimorphism, age, the year of
116 publication and study quality. We addressed the primary and secondary objectives by conducting
117 correlational meta-analyses and group comparisons, respectively. To address potential moderators
118 of the presumed relationship between vagally-mediated resting-state HRV and executive
119 functioning, we conducted meta-regression analyses.

120

121 **Materials & Methods**

122 Throughout the meta-analytic process, we followed the recommendations of the Preferred
123 Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA, see Liberati et al., 2009;
124 Moher et al., 2009) statement and recent recommendations for conducting correlational meta-
125 analyses (Quintana, 2015).

126 **Systematic literature search**

127 A systematic literature search was performed to identify studies reporting on vagally-mediated
128 resting-state HRV in association with executive functioning. Only studies assessing the three main
129 components of executive functioning (i.e., cognitive flexibility, updating in working memory, and
130 cognitive inhibition, see(Miyake et al., 2000)) either in a composite task or separately and that used
131 time- or frequency-domain measures or RSA to extract vagally-mediated HRV were included. A
132 broad search strategy (Supplementary material 1) was formulated and employed a combination of
133 keywords: (cognit* OR neuropsycholog* OR “executive function*” OR “cognitive inhibition” OR
134 “cognitive flexibility” OR “updating of working memory”) AND (HRV OR “heart rate variability”
135 OR “vagal tone” OR “vagal activity”) in PsycINFO, PubMed, Embase, ScienceDirect and

136 Cochrane library. The following constraints were applied to limit search results: (1) articles on
137 adults (>18 years), (2) written in English, and (3) original research articles (excluding reviews and
138 meta-analysis). Identical search terms were employed in all database searches. For some databases
139 (e.g. ScienceDirect) that have a limitation on the number of keywords used in the search equation,
140 we had to adapt the search equation to use all terms from the main equation. In addition, the
141 reference lists of included publications identified through database searches were screened for
142 additional relevant articles. Searches were conducted on July 9, 2021, to May 31, 2022 (for
143 additional articles). Two authors (Valentin Magnon, Guillaume Vallet) conducted the literature
144 searches, reviewed the abstracts, and based on the selection criteria, decided the suitability of
145 the articles for inclusion, and extracted the data. When necessary, disagreements were solved with
146 a third author (Frédéric Dutheil).

147 **Inclusion of eligible studies**

148 We included only correlational studies in the current systematic review and meta-analysis to
149 control the issue of the variability of study designs and methodological procedures previously
150 identified (Forte et al., 2019). To be included, studies needed to report a correlation analysis
151 between vagally-mediated resting-state HRV (i.e., RMSSD, RSA, or HF) and performance on tasks
152 evaluating executive functioning in healthy adults. Studies reporting regression analyses were
153 included only if vagally-mediated resting-state HRV was the main predictor of executive
154 functioning as a dependant variable and if the effect size (ES) was stated. Procedures of extraction
155 of HRV from inter-beat interval data and analyses were carried out in accordance with the approved
156 recommended guidelines for assessing HRV variables in psychophysiological research (Laborde
157 et al., 2017; Quintana & Heathers, 2014; Task Force Report, 1996).

158 Data extraction and management

159 ES and sample sizes were extracted from eligible studies. When data were not provided, the
160 corresponding author of the publication was contacted. By using a digital data extraction sheet, the
161 following data were extracted if available: general information and identifying features of the study
162 (full reference, author names, the journal, and year of publication), descriptive data (sample
163 population, size, age, sex and body mass index as it was the most frequently controlled variable
164 provided), measures of executive functioning (neuropsychological test used and corresponding
165 executive component assessed, main outcomes, reaction times, error rate, accuracy or composite
166 scores), HRV measurement (frequency- or time-domain, RMSSD, HF or RSA, the recording length
167 and device used), results (correlation coefficient or regression effect size to be converted).

168 Study quality assessment

169 The risk of bias was defined as a measure of risk for a biased estimation of the association between
170 vagally-mediated HRV and executive functioning. As there are few reliable and validated tools
171 available to appropriately assess the risk of bias in included correlational studies, we relied on two
172 assessment tools for greater validity. Therefore, to assess the quality and possible risk of bias in
173 correlational studies, we used the National Institutes of Health (NIH) Quality Assessment Tool for
174 Observational Cohort and Cross-Sectional Studies (Ma et al., 2020; National Institutes of Health,
175 2014) in combination with the Strengthening the Reporting of Observational Studies in
176 Epidemiology (STROBE) guidelines (Vandenbroucke et al., 2007). The quality of a study was
177 considered poor, fair, or good when the study met less than 5, between 5 and 8, and more than 8 of
178 the NIH Quality Assessment Tool criteria, respectively (Supplementary material 2). As the
179 STROBE checklist is not strictly speaking a risk of bias assessment tool (Costa et al., 2011), it was
180 used to corroborate the NIH Quality Assessment Tool criteria.

181 **Statistical analysis**

182 Statistical analysis were performed with RStudio software version 3.6.3(RStudio Team, 2020),
183 using the *meta*(Schwarzer, 2021), *metafor*(Viechtbauer, 2021), and *dmetar*(Harrer et al., 2021a) R
184 packages. Raw ES were transformed to Fisher's z for variance stabilization (Harrer et al., 2021b).
185 A random effects model(DerSimonian & Kacker, 2007; Higgins et al., 2009), where between-
186 studies variance (τ^2) was estimated using a restricted maximum likelihood method as
187 recommended for continuous outcomes(Veroniki et al., 2016), was used in the synthesis of
188 individual ES into a summary ES.

189 In order to test whether a specific HRV measurement better predicted executive functioning than
190 other measures and if a specific executive function was predicted more by vagally-mediated HRV
191 than the others, we performed subgroup meta-analyses according to vagally-mediated HRV
192 parameters (RMSSD *vs.* HF *vs.* RSA) then according to executive functions (cognitive functioning
193 *vs.* cognitive inhibition *vs.* updating in working memory *vs.* global composite executive score)
194 respectively.

195 Meta-regressions were then conducted to test potential moderators which were defined *a priori*.
196 The vagally-mediated HRV parameters and the executive functions were included in the regression
197 model as two categorical predictors to test possible interaction terms. Permutation tests were also
198 conducted as they have been recommended to assess the robustness of the meta-regression
199 models(Higgins & Thompson, 2004). Age, sex distribution, the year of publication, and study
200 quality (indicated by NIH Quality Assessment scores) were tested as continuous predictors. The
201 Knapp-Hartung method(IntHout et al., 2014) and method of restricted maximum
202 likelihood(Langan et al., 2019) were used for meta-regression analyses.

203 For all statistical analyses, the employed statistical significance threshold was set at $p < 0.05$. To
204 assess the observed variance and heterogeneity in the true ES between included studies, the
205 significance of Cochran's Q (Cochran, 1954) and Higgins & Thompson's I^2 statistic(Higgins &
206 Thompson, 2002) were computed. I^2 values of ~25%, ~50%, and ~75% were interpreted as low,
207 moderate, and high heterogeneity between studies(Higgins et al., 2003). A Baujat plot (Baujat et
208 al., 2002) enabled the detection of ES which overly contribute to the heterogeneity in order to
209 remove them if heterogeneity $> 50\%$. Furthermore, in order to identify potential ES outliers, outlier
210 diagnostics were performed (Viechtbauer & Cheung, 2010). Next, the conventional Egger's
211 regression test was applied(Egger et al., 1997) to investigate whether the presence of small-study
212 effects(Sterne et al., 2000) is likely (Egger's regression test: $p < 0.05$) or not. As a further model
213 diagnostic, variants of the funnel plot (including contour-enhanced) were created to investigate the
214 likelihood of a publication bias as well (Schmucker et al., 2014). Funnel plots traditionally illustrate
215 the distribution of ES estimates by their standard errors including an idealized funnel-shape
216 centered on the summary ES. Contour enhanced funnel plot superimposes key areas of statistical
217 significance ($p = 0.1$, $p = 0.05$, $p = 0.01$) to assess for risk of publication bias (indicated by over-
218 representation of ES in areas of significance). When there is no publication bias, studies should
219 roughly follow the shape delineated by the funnel displayed in the plot and the data points should
220 form a roughly symmetrical, upside-down funnel(Harrer et al., 2021a). However, asymmetry of
221 the funnel plot can be caused by very different mechanisms, and should not be readily attributed to
222 publication bias(Doleman et al., 2020). Once the outliers were removed, the meta-analysis was
223 conducted again, along with subgroup analyses and meta-regressions.

224

225 **Results**

226 The searches resulted in a total of 16,675 studies. Based on the title, irrelevant articles and
227 duplicates were removed to obtain 1,306 articles that were then screened based on the abstract.
228 Then, 37 studies were assessed for eligibility. After full-text reading, 13 articles were included in
229 the present systematic review and meta-analysis (Fig. 1). In this meta-analysis, 13 studies yielding
230 52 ES were included (Capuana et al., 2014; Colzato et al., 2018; Colzato & Steenbergen, 2017;
231 Hansen et al., 2003; Kaufmann et al., 2012; Keen et al., 2020; Mathewson et al., 2010; Ottaviani
232 et al., 2019; Spangler et al., 2018; Stenfors et al., 2016; D. P. Williams et al., 2016; P. G. Williams
233 et al., 2019; Xing et al., 2020). Characteristics of studies are presented in Table 1.

234 **Study quality**

235 All studies have been assessed as either fair (Capuana et al., 2014; Colzato & Steenbergen, 2017;
236 Kaufmann et al., 2012; D. P. Williams et al., 2016) or good quality (Colzato et al., 2018; Hansen et
237 al., 2003; Keen et al., 2020; Mathewson et al., 2010; Ottaviani et al., 2019; Spangler et al., 2018;
238 Stenfors et al., 2016; P. G. Williams et al., 2019; Xing et al., 2020) based on the validated NIH
239 Quality Assessment Tool (Fig. 2). This was further supported by the STROBE checklist according
240 to which all studies presented overall good quality (scores $\geq 19/27$).

241

242 **Characteristics of population**

243 The total number of participants included was 998: 411 men (41%) and 587 women (59%). The
244 proportion of men varied from 21% (Stenfors et al., 2016) to 100% (Hansen et al., 2003). The mean
245 age of participants was 24.6 years old ranging from 18 (Xing et al., 2020) to 48 years old (Stenfors
246 et al., 2016). Nine studies were conducted on undergraduates students (Capuana et al., 2014;
247 Colzato et al., 2018; Colzato & Steenbergen, 2017; Kaufmann et al., 2012; Keen et al., 2020;

248 Spangler et al., 2018; D. P. Williams et al., 2016; P. G. Williams et al., 2019; Xing et al., 2020),
249 one study (Mathewson et al., 2010) on young participants recruited at the university,
250 another(Ottaviani et al., 2019) on young adults recruited from the general population and one
251 study(Hansen et al., 2003) on male sailors from the Royal Norwegian Navy. Only one
252 study(Stenfors et al., 2016) was conducted on middle-aged working adults. Only six studies
253 reported body mass index(Colzato et al., 2018; Colzato & Steenbergen, 2017; Keen et al., 2020;
254 Ottaviani et al., 2019; Spangler et al., 2018; P. G. Williams et al., 2019). The mean body mass
255 index was 23.7 kg/m² ranging from 17.2 to 44.0(P. G. Williams et al., 2019). Only two studies
256 reported anxiety levels(Colzato et al., 2018; Colzato & Steenbergen, 2017), and only one reported
257 education level(Stenfors et al., 2016). Despite six studies controlling for smoking(Colzato et al.,
258 2018; Mathewson et al., 2010; Ottaviani et al., 2019; Spangler et al., 2018; D. P. Williams et al.,
259 2016; P. G. Williams et al., 2019), five for coffee consumption (Mathewson et al., 2010; Ottaviani
260 et al., 2019; Spangler et al., 2018; D. P. Williams et al., 2016; P. G. Williams et al., 2019), three
261 for alcohol intake (Ottaviani et al., 2019; Spangler et al., 2018; P. G. Williams et al., 2019), two
262 for the medication(Capuana et al., 2014; Ottaviani et al., 2019), those data were seldomly reported.
263 Participants were asked to not use those substances 2 to 6 hours before the experiment, as well as
264 to refrain from engaging in moderate or vigorous physical activity(Ottaviani et al., 2019; D. P.
265 Williams et al., 2016; P. G. Williams et al., 2019).

266 **Meta-analysis on the association between vagally-mediated HRV and executive functioning**

267 The meta-analysis revealed a small positive correlation between vagally-mediated HRV and
268 executive functioning ($r = 0.15$, 95% CI 0.09 to 0.21, $p < 0.0001$, $k = 52$), with a I^2 of 65%. A
269 subgroup analysis showed significant differences between HRV parameters ($p < 0.05$). A moderate
270 positive ES estimate were observed for RSA ($p < 0.001$) while a small positive ES were revealed

271 for RMSSD ($p < 0.01$) and HF ($p < 0.01$). ES for RSA were larger than for RMSSD ($p < 0.05$). HF
272 did not differ from RMSSD ($p = 0.42$) and HF was marginally smaller than RSA ($p = 0.09$).
273 Another subgroup analysis based on executive functions indicated positive small ES for cognitive
274 inhibition ($p < 0.001$) and cognitive flexibility ($p < 0.001$), a negative ES for global executive
275 functioning ($p < 0.05$) and no significant ES for working memory ($p = 0.16$). ES significantly
276 differed across executive functions ($Q_b(3) = 19.86, p = 0.0002$). ES for cognitive inhibition were
277 significantly larger than ES for global executive functioning ($p < 0.001$) and working memory (p
278 < 0.001) whereas they did not differ from ES for cognitive flexibility ($p = 0.78$). Similarly, ES
279 estimates for cognitive flexibility were significantly larger than ES for global executive functioning
280 ($p < 0.001$) and working memory ($p < 0.05$). ES were also larger for working memory than for
281 global executive functioning ($p < 0.01$). The small number of ES ($k = 4$) and high heterogeneity
282 ($I^2 = 92\%$) for global executive functioning severely limits the interpretation of the results for this
283 subgroup. There was no evidence of an interaction term between HRV parameters and executive
284 functions ($F(3, 43) = 0.52, p = 0.67$) (see all statistical details in Supplementary material 3).

285

286 **Sensitivity analyses**

287 The Egger's test was significant ($p = 0.01$). Furthermore, the chi-square Q -statistic (Cochran's Q
288 test for heterogeneity) exceeded the level of significance ($Q_{51} = 146.1, p < 0.0001$) assuming that
289 variation in ES estimates was not caused by sampling error alone. Therefore, 65 % of the variance
290 in ES estimates was due to true variation among studies rather than mere sampling error. Since it
291 assumes that more than half of the variation was due to true ES differences (Higgins & Thompson,
292 2002), outlier diagnostics were performed. Six ES from 4 studies (Hansen et al., 2003; Keen et al.,
293 2020; Stenfors et al., 2016; Xing et al., 2020) were distributed outside of the idealized funnel-shape
294 centered on the summary ES (Fig. 3) and were removed from further analyses. The meta-analysis

295 conducted without outliers confirmed a positive correlation between vagally-mediated HRV and
296 executive functioning ($r = 0.19$, 95% CI 0.15 to 0.23, $p < 0.0001$, $k = 46$; Fig. 4) with low
297 heterogeneity between true ES ($I^2 < 25\%$). As such, this new model was retained as the most
298 robust analyses (Table 2).

299 Significant differences between HRV parameters (Fig. 5) were revealed by subgroup analysis
300 ($Q_b(2) = 13.13$, $p = 0.0014$). Moderate positive ES estimates were observed for RSA ($k = 8$, $\beta =$
301 0.40 , 95% CI 0.25 to 0.54, SE = 0.07, $p < 0.0001$), while small positive ES were revealed for
302 RMSSD ($k = 20$, $\beta = 0.21$, 95% CI 0.15 to 0.26, SE = 0.03, $p < 0.0001$) and HF ($k = 18$, $\beta = 0.14$,
303 95% CI 0.09 to 0.19, SE = 0.03, $p < 0.0001$). ES estimates for RSA were larger than for HF ($\beta =$
304 0.26 , 95% CI 0.10 to 0.41, SE = 0.08, $p = 0.0018$) and for RMSSD ($\beta = 0.19$, 95% CI 0.03 to 0.35,
305 SE = 0.08, $p = 0.0164$). ES for RMSSD did not differ from ES for HF ($\beta = 0.06$, 95% CI -0.01 to
306 0.14 , SE = 0.04, $p = 0.08$). Similarly, subgroup analysis based on executive functions (Fig. 5)
307 revealed significant differences between subgroups ($Q_b(3) = 19.37$, $p = 0.0002$) indicating positive
308 small ES for cognitive inhibition ($k = 24$, $\beta = 0.21$, 95% CI 0.16 to 0.26, SE = 0.03, $p < 0.0001$),
309 cognitive flexibility ($k = 10$, $\beta = 0.23$, 95% CI 0.16 to 0.30, SE = 0.03, $p < 0.0001$) and working
310 memory ($k = 11$, $\beta = 0.08$, 95% CI 0.02 to 0.15, SE = 0.03, $p = 0.008$). There was only one ES
311 estimate for global cognitive functioning composite score severely limiting the interpretation of
312 the results for this subgroup ($k = 1$, $\beta = 0.41$, 95% CI 0.19 to 0.64, SE = 0.11, $p = 0.0007$). ES
313 estimates for cognitive inhibition and cognitive flexibility were larger than for working memory (β
314 $= 0.13$, 95% CI 0.05 to 0.21, SE = 0.04, $p = 0.0019$; $\beta = 0.14$, 95% CI 0.05 to 0.23, SE = 0.05, p
315 $= 0.0027$ respectively). No differences in ES estimates were observed between cognitive inhibition
316 and cognitive flexibility ($\beta = 0.01$, 95% CI -0.07 to 0.10, SE = 0.04, $p = 0.75$). Further exploratory
317 analyses did not reveal an interaction between executive functioning component and vagally-
318 mediated HRV measurements ($F(2, 38) = 0.67$, $p = 0.52$).

319 **Impact of other possible moderators on effect size**

320 A Meta regression analysis model revealed that age negatively influenced ES ($\beta = -0.005$, 95 % CI
321 -0.008 to -0.002 , SE = 0.001, $p = 0.005$) while there was no evidence that the proportion of males
322 in the sample had a significant effect on effect size ($\beta = 0.0001$, 95% CI -0.002 to 0.003 , SE =
323 0.001 , $p = 0.94$). BMI did not influence effect size either ($\beta = 0.01$, 95 % CI -0.04 to 0.07 , SE =
324 0.03 , $p = 0.65$). In addition, meta-regression analysis revealed that neither study quality ($\beta = -0.03$,
325 95 % CI -0.09 to 0.03 , SE = 0.03, $p = 0.34$) nor year of publication ($\beta = -0.003$, 95 % CI -0.01 to
326 0.01 , SE = 0.01, $p = 0.63$) influenced effect size (Fig 6).

327

328 **Discussion**

329 The objective of the present systematic review and meta-analysis was to provide a better
330 understanding of how HRV might be related to executive functioning. A small positive correlation
331 was revealed between vagally-mediated HRV and executive functioning. This finding supports the
332 association between vagally-mediated HRV and executive functioning predicted by the
333 neurovisceral integration model(Thayer et al., 2009). The vagus nerve might be the
334 psychophysiological pathway to the activity of the prefrontal cortex and the anterior cingulate
335 cortex involved in the regulation of inhibitory/self-regulatory abilities and thus executive
336 functioning(Thayer et al., 2012). The relationship between vagally mediated HRV and executive
337 functioning appears to depend on the HRV parameter assessed, the executive function measured,
338 and the age of the participants.

339 **Moderating effect of vagally-mediated HRV parameters**

340 Interestingly, while all vagally-mediated HRV parameters correlated with executive functioning,
341 the association between RSA and executive functioning was moderate while the correlation

342 between HF or RMSSD and executive functioning was significantly smaller. From a theoretical
343 standpoint, one possible explanation is that RSA may be a reliable index of self-regulatory abilities.
344 RSA reflect the respiration-driven increasing and decreasing of the heart, *via* the vagus nerve, made
345 possible by the baroreflex(Karemaker, 2009; Shaffer & Ginsberg, 2017). As such, it reflects the
346 adjustment of the heart rate by the vagus nerve according to respiration rate. Under the right
347 circumstances (spontaneous breathing), RSA may index the adaptation of the vagus nerve to an
348 external factor, i.e. respiration rate, and thus the self-regulatory capacities of the vagus nerve. In
349 this hypothesis, RSA would not reflect vagal activity as such (usually assessed by the power
350 spectrum density of HF band or RMSSD) but rather how well vagal activity is regulated by the
351 vagus nerve in accordance with respiration rate. Previously, a review suggested that RSA is
352 essential in self-regulation as it plays a primary role in the regulation of energy exchange by
353 synchronizing respiratory and cardiovascular processes during metabolic and behavioral
354 change(Grossman & Taylor, 2007). However, it was noted that, under certain circumstances
355 (longer exhalations allowing greater acetylcholine metabolism), slower respiration rates can
356 produce higher RSA amplitudes that are not mediated by changes in vagal firing(Shaffer &
357 Ginsberg, 2017). As none of the articles included in the present systematic meta-analysis
358 manipulated respiration rate, RSA in those articles should reflect vagally-mediated changes in heart
359 rate. Supporting the importance of changes in vagal activity rather than vagal activity as such, the
360 vagal tank theory (Laborde et al., 2018) suggests that vagal reactivity to, and recovery from, a
361 specific extern event (beyond the influence of respiration rate such as undertaking a cognitively
362 engaging task) are relevant to index self-regulatory abilities.

363 Moderating effect of specific executive functions

364 The results suggest that the adaptability and flexibility of the vagus nerve might directly relate to
365 the corresponding executive functions. Indeed, regarding the executive functions tested, vagally-
366 mediated HRV correlated more with cognitive inhibition and cognitive flexibility than with
367 updating in working memory, however, all associations were small. In support of this idea, it has
368 been proposed that vagally-mediated HRV is particularly associated with performance on goal-
369 directed tasks involving adaptive psychological regulation and flexible cognitive processes
370 (involving cognitive inhibition and cognitive flexibility), whereas tasks inducing mental stress (i.e.,
371 working memory tasks) are associated with decreased vagal-mediated HRV(G. Park et al., 2014).
372 More precisely, working memory would require more cognitive engagement resulting in
373 sympathetic predominance to manage mental stress(Duschek et al., 2009). In contrast, tasks
374 involving cognitive inhibition or cognitive flexibility require greater self-regulatory effort
375 associated with parasympathetic activity (G. Park et al., 2014; Segerstrom & Nes, 2007). The
376 polyvagal theory proposes an evolutionary point of view to interpret the role of the autonomic
377 nervous system in cognitive functioning according to contextual cues (Porges, 2007). According
378 to this theory, the autonomic nervous system has evolved to promote the focus of attention
379 (sympathetically-driven) in threatening situations and cognitive flexibility processes
380 (parasympathetically-driven) in secure situations to favor social cognition and increase the odds of
381 survival. Taken together, these findings suggest that the adaptability of the vagal inhibitory cardiac
382 control is directly related to adaptative cognitive processes, mainly cognitive inhibition and
383 flexibility.

384 Moderating effect of age

385 The relationship between vagally-mediated HRV and executive functioning may however be
386 influenced by several factors, including age. Specifically, age negatively predicted the strength of
387 this relationship in the studied population ranging from 18 to 66 years old. Middle-aged adults
388 seem to have some difficulties with certain executive functioning tasks(Ferguson et al., 2021).
389 Concurrently, vagally-mediated HRV seems to decrease linearly with age and then the reverse with
390 an increase in those above 60 years old(Geovanini et al., 2020). Concomitant vagal and executive
391 declines support the direct association between vagal activity and prefrontal brain areas involved
392 in executive functioning, which may play a role in cognitive aging(Thayer et al., 2021). In line with
393 the bidirectional heart-brain axis hypothesis, the reverse vagal increase observed after 60 years old
394 might be the physiological compensation mechanism underpinning the greater cerebral activation
395 observed in the prefrontal cortex in older people to achieve equivalent cognitive performances to
396 those of younger adults(Cabeza et al., 2002, 2004). However, the cerebral integration of cardiac
397 information seems to decline with age(Khalsa et al., 2009; Murphy et al., 2018). The insular cortex
398 is a key area in the cerebral integration of visceral signals including those from the cardiovascular
399 system(Aleksandrov & Aleksandrova, 2015; Craig, 2009; Damasio & Carvalho, 2013). Aging is
400 associated with grey matter loss in the insular cortex(Resnick et al., 2003) possibly explaining the
401 decreased strength of the heart-brain bidirectional interactions with age. It has previously been
402 reported that substantial sex differences existed in vagally-mediated HRV(Koenig & Thayer,
403 2016). Specifically, women seem to have lower total power in the spectral density than men and,
404 while women show less power in the very-low and LF bands, they show greater power in the HF
405 band than men. Interestingly, despite greater vagal activity in women, there was no evidence of sex
406 differences in the association between vagally-mediated HRV and executive functioning in the

407 present meta-analysis; suggesting that the physiological mechanisms underlying heart-brain
408 interactions might be similar in men and women.

409 **Limitations and current challenges**

410 Interpretations of the current results must be nuanced as the present systematic meta-analysis is not
411 without limitations. First, the nature of this meta-analysis is correlational, thus no causal
412 conclusions can be drawn. In addition, despite a large number of included effect sizes, there were
413 only eight ES estimates for updating in working memory and one for global executive functioning
414 limiting the interpretations of the results for those subgroups. Furthermore, we conducted the meta-
415 analyses only on published articles, so they are theoretically exposed to a possible publication bias.
416 The few studies conducted on aging populations were not included as older people have very
417 different profiles due to developmental trajectories which could have generated heterogeneity
418 between studies. For instance, as far as vagal activity is concerned, some data indicate that older
419 individuals can linearly maintain high HRV (Tan et al., 2019), others suggest that HRV decreases
420 with age before increasing around 65 years old as a U shape developmental trajectory (Almeida-
421 Santos et al., 2016) while others rapport linear decline in HRV with age (Reardon & Malik, 1996).
422 A meta-analysis inherits also the limitations and biases of the individual studies investigated.
423 Indeed, several methodological issues were identified in the included studies through the
424 systematic review process, despite good overall methodological quality following
425 recommendations for conducting research on HRV(Laborde et al., 2017; Quintana & Heathers,
426 2014), with the length of the recording (5-6 min.) adequate for short-term HRV recording(Li et al.,
427 2019; Shaffer & Ginsberg, 2017) and the accuracy of the recording devices validated and reliable,
428 especially when the recording occurs at rest (for the validation of the Polar H7, see Hernández-
429 Vicente et al., 2021; for a general review see Ishaque et al., 2021). While several studies use ECG

430 to assess the relationship (through correlations) between heart rate variability and cognitive
431 variables, the directionality of the observed effect remains uncertain. The potential causality in this
432 relationship could be further investigated with other methodologies that require the recording of
433 brain oscillations through electroencephalography (EEG) in addition to the heart activity recording
434 within a framework of mutual influence (Candia-Rivera, Catrambone, et al., 2021). Nonetheless,
435 the small summary ES may reflect that some of the included studies are underpowered. Only two
436 studies (Spangler et al., 2018; Xing et al., 2020) have conducted *a priori* power analysis(Cohen,
437 2013). Another main issue was that several factors likely to influence either cardiovascular
438 functioning or cognitive functioning or both were not always controlled. Besides age and sex
439 distribution which were always reported, the most controlled and reported variable was body mass
440 index(Colzato et al., 2018; Colzato & Steenbergen, 2017; Keen et al., 2020; Ottaviani et al., 2019;
441 Spangler et al., 2018; P. G. Williams et al., 2019) followed by smoking(Colzato et al., 2018;
442 Mathewson et al., 2010; Ottaviani et al., 2019; Spangler et al., 2018; D. P. Williams et al., 2016;
443 P. G. Williams et al., 2019) and caffeine intake(Mathewson et al., 2010; Ottaviani et al., 2019;
444 Spangler et al., 2018; D. P. Williams et al., 2016; P. G. Williams et al., 2019). However, some
445 lifestyle factors that may influence executive functioning or HRV were not considered in the
446 studies included in this review, such as diet(Martínez-Lapiscina et al., 2013; Millman et al., 2021),
447 sleep quality(Bourdillon et al., 2021; Rana et al., 2018) and sedentariness(Magnon, Vallet, et al.,
448 2018, 2021; Zaffalon Júnior et al., 2018) recognized as a risk factor independent of physical
449 inactivity(Magnon, Dutheil, et al., 2018; Panahi & Tremblay, 2018). Finally, it is recommended
450 that cognitive function is evaluated by two different measures(Hebben & Milberg, 2009) whereas
451 only one test has often been used to assess a specific executive function in the included studies.
452 Moreover, certain tests might not be the most appropriate for the studied population. For instance,
453 since the 2-back version of the n-back induced a relatively low cognitive engagement level in a

454 young population compared to the 3-back version (Herff et al., 2014), the difficulty might not be
455 high enough for undergraduates students(Dong et al., 2015). The heterogeneity between studies in
456 cognitive measurements might also explain the small effect size of the overall association between
457 HRV and executive performance. One can imagine that if the same tests were used to assess a
458 specific executive function, the association between HRV and executive functioning would have
459 been stronger than the one observed in the present study. Nonetheless, the results of this systematic
460 review and meta-analysis are in line with the neurovisceral integration model(G. Park & Thayer,
461 2014; Thayer et al., 2009) and embodied cognitive sciences(Badcock et al., 2019; Pezzulo & Cisek,
462 2016; Seth, 2013) suggesting that visceral information may underpin executive functioning to some
463 extent. From a clinical perspective, if the heart-brain axis interactions are further empirically
464 supported, breathing exercises are efficient, cheap and simple to increase vagally-mediated
465 HRV(Magnon, Dutheil, et al., 2021; Van Diest et al., 2014) which could possibly enhance cognitive
466 functioning(De Couck et al., 2019; Zaccaro et al., 2018) and thus could be used as a way to prevent
467 cognitive difficulties associated with chronic pathologies and aging.

468 **Further recommendations**

469 In order to address the identified methodological issues and to ensure a greater methodological
470 validity of studies investigating the association between vagally-mediated HRV and executive
471 functioning, we suggest nine recommendations below organized in order of importance.

- 472 1. **ECG or validated non-invasive recording devices.** It is recommended to prioritize ECG
473 when possible as it is the gold standard to accurately record inter-beat interval values.
474 Interestingly, EEG in complement of ECG can be used to assess the brain and heartbeat
475 oscillations respectively within a framework of mutual influence that may allow for
476 causality assessment (e.g. physiological modeling approaches, see Candia-Rivera,
477 Catrambone, et al., 2021). When other recording devices are used, we recommend to cite

478 articles validating their accuracy and reliability as non-standardized recording devices can
479 cloud interpretation and generalizability of findings (Nelson et al., 2020).

- 480 2. **Definition of the HRV measurement used in relation to the research question.** Since
481 there is an ongoing debate about the theoretical interpretation of several HRV indices
482 (Berntson et al., 2005; Hayano & Yuda, 2019; Karemaker, 2009), the theoretical definition
483 of the HRV index measured should be defined *a priori* and clearly stated as well as its
484 relevance for the research question. Furthermore, the formula for calculation of the HRV
485 index and the data analysis software used should be indicated. For instance, the calculation
486 of the HF band is not always reported, yet it can be expressed in many units such as m^2 ,
487 Hz, normalized units (n.u.), and in the percentage of the total power (Tarvainen et al., 2014).
- 488 3. **Power analysis.** Conducting a power analysis can be difficult for pilot and exploratory
489 studies that investigate a new research question that was not previously addressed since
490 there are no studies on which the power analysis can be based on. However, when previous
491 studies addressing similar research questions exists, a power analysis can be conducted
492 easily using free software such as Gpower (Faul et al., 2009) or the *pwr* R package
493 (Champely et al., 2020) ensuring sufficient sample size.
- 494 4. **Homogeneity of the sample.** The target population should be as homogeneous as possible
495 to control for the possible influence of variables such as prior cardiovascular illnesses (e.g.
496 arrhythmia, heart failure), severe inflammation (e.g. arthritis), or a neurological (head
497 trauma, epilepsy, etc.), physiological (hypo- or hyperthyroidism, type 2 diabetes) or
498 neurodevelopmental disorder (autism, dyslexia, etc.). In addition, several lifestyle factors
499 should be controlled and reported when possible: age, sex distribution, the body mass index,
500 caffeine, alcohol, nicotine, medication, other substances consumption, anxiety level,

501 depression level, education level, physical activity level, sedentary time, diet, sleep quality
502 (Quintana & Heathers, 2014).

503 5. **Instructions priors to the experimental session.** It is recommended to give prior
504 instructions to refrain the participants from engaging in any behaviors that might affect
505 variables of interest before the experimental session (6 hours before if possible).

506 6. **10 minutes of rest before baseline HRV.** We recommend that the participant rest 10
507 minutes before baseline to ensure resting state HRV is assessed, which is rarely
508 implemented.

509 7. **Resting, Reactivity, and Recovery.** Even if resting HRV has been the most investigated
510 parameter in relation to executive functioning, certain associations might reveal themselves
511 only when considering vagal reactivity (e.g., Calkins et al., 2007). As such, it is
512 recommended to assess during at least 5 minutes (Malik et al., 1996) vagally-mediated
513 HRV before (rest), during (reactivity) and after (recovery) a cognitive task (Laborde et al.,
514 2018).

515 8. **Neuropsychological tests.** The neuropsychological tests to assess executive functioning
516 used must be valid, reliable, and sensitive. We recommended the use of standardized tests
517 commonly recognized among researchers in cognitive psychology or neuropsychology, as
518 well as, using ideally two different measures to evaluate one cognitive function (Hebben &
519 Milberg, 2009).

520 9. **Control of respiration.** When RSA or HF is assessed, we recommended to do so in a
521 resting state without manipulating respiration rate (spontaneous breathing) or by controlling
522 for respiratory rate. It was suggested that, under certain circumstances, respiration rate
523 changes can produce large-scale shifts in RSA magnitude without affecting vagal tone
524 (Shaffer & Ginsberg, 2017).

525 These recommendations can also be applied when studying the role of the heart-brain relationship
526 beyond executive functioning, as it is studied in many other cognitive domains (see Zahn et al.,
527 2016). For example, recent studies have addressed the long-standing debate about the role of
528 bodily activity in emotion (Pace-Schott et al., 2019), attempting to propose an answer by showing
529 that autonomic cardiac activity could play a leading and causal role in initiating emotional states
530 (Candia-Rivera, Catrambone, et al., 2021). Interestingly, rather than investigating the role of heart-
531 brain interaction in emotion, other studies have recently examined the role of a pre-existing
532 emotional state in the involvement of heart-brain interaction in cognition. For example, induced
533 sadness influences the association between HRV and cognitive inhibition (Hoffmann et al., 2022).
534 Beyond emotional processing, other studies focused on the interplay between heart and brain in
535 perception, showing that cardiac activity might influence the attention afforded to external signals
536 and the preparation of an appropriate course of action (Skora et al., 2022). In a broader way,
537 autonomic activity has also been studied in relation to consciousness generation (Candia-Rivera,
538 Annen, et al., 2021), leading to the hypothesis that ascending bodily signals into neural systems
539 could a switch for consciousness (Sattin et al., 2020).

540 **Conclusion**

541 In this first systematic review and meta-analysis of studies reporting data on a potential link
542 between vagally-mediated HRV and executive functioning, we provide some evidence that 1)
543 vagally-mediated HRV is associated with executive functioning; 2) RSA may be more strongly
544 associated with executive functioning than RMSSD and HF; 3) vagally-mediated HRV correlates
545 more with cognitive flexibility and cognitive inhibition than with updating in working memory; 4)
546 age negatively moderates the relationship between vagally-mediated HRV and executive
547 functioning. Our results are in line with the neurovisceral integration model suggesting that visceral

548 information may underpin executive functioning to some extent. Several methodological issues
549 which may account for the small associations observed in the present meta-analysis were identified
550 and discussed. Future quality studies addressing these methodological issues would be necessary
551 to refine the conclusions drawn from these initial results.

Journal Pre-proof

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563 **Data availability statement**

564 The data supporting the conclusions of this article are available at: <https://osf.io/fuhwt>

565

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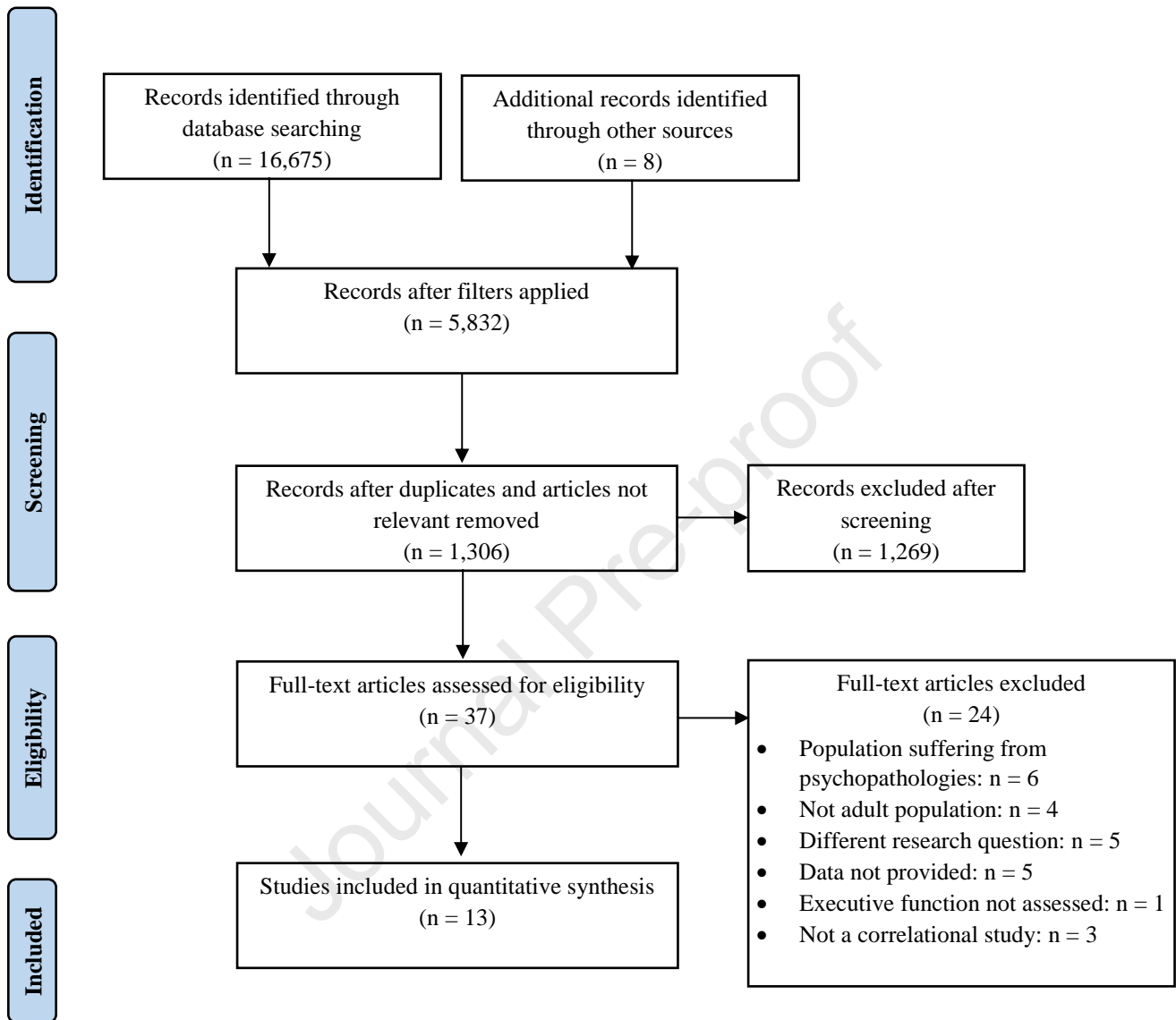


Fig. 1. PRISMA Flow Diagram depicting the study selection process.

Table 1

Summary characteristics of included studies.

Study	Quality NIH (Strobe)	Population Type	Population				Executive functioning				Pearson' <i>r</i>	HRV recording		
			n	Age*	Men/Women	BMI*	Function	Assessment	Outcomes	Index		Length	Device	
Capuana et al., 2014	Fair (23)	Undergraduate students	17	21.1 [18-26]	6/11	-	Cognitive inhibition	Stroop task	Accuracy score	0.39	RSA	5 min	ECG	
								Stroop task (Incentive)	Accuracy score	0.51				
								Memory Stroop task	Accuracy score	0.57				
								Memory Stroop task (Incentive)	Accuracy score	0.54				
								Repeat Stroop task	Accuracy score	0.19				
								Repeat Stroop task (Incentive)	Accuracy score	0.31				
Colzato & Steenbergen, 2017	Fair (20)	Undergraduate students	88	21.2 [18-33]	50/38	22.17 [18-30]	Cognitive inhibition	Stop-change task: 0 ms delay stop - change.	Reaction time	-0.23	RMSSD	5 min.	Polar H7	
								Stop-change task: 300 ms delay stop - change.	Reaction time	-0.18				
Colzato et al., 2018	Good (20)	Undergraduate students	90	22.1 (2.5)	30/60	23.4 (3.7)	Cognitive flexibility	Task switching: short delay response - stimulus	Reaction time	-0.294	HF	5 min.	Polar H7	
								Task switching: long delay response - stimulus	Reaction time	-0.252				
								Task switching	Overall index	-0.168				
								Task switching: short delay response - stimulus	Reaction time	-0.295				
								Task switching: long delay response - stimulus	Reaction time	-0.246				
								Task switching	Overall index	-0.156				
Hansen, Johnsen, & Thayer, 2003	Good (19)	Male sailors from the Royal Norwegian Navy	53	23 [18-34]	53/0	-	UWM	2-back task	Correct responses	0.23	RMSSD	5 min.	AMS	
									Error rate	0.22				
									Miss responses	-0.24				
								Continuous performance test	Error rate	-0.23				

Study	Quality NIH (Strobe)	Population					Executive functioning			Pearson' <i>r</i>	HRV recording		
		Type	n	Age*	Men/Women	BMI*	Function	Assessment	Outcomes		Index	Length	Device
Kaufmann et al., 2012	Fair (20)	Undergraduate students	34	26.3 (6.1) [18-44]	16/18	-	Cognitive inhibition	Visual P300 spelling matrix	Accuracy score Accuracy score Accuracy score	0.51 0.24 0.40	RSA RMSSD HF	5 min.	ECG
Keen, Tan, & Abbate, 2020	Good (23)	Undergraduate students	92	20.32 (2.28)	25/67	25.66 (6.52)	Global executive functioning	Berg Card Sorting Test	Completion speed Correct responses Total errors	-0.40 -0.40 0.41	RMSSD	5 min.	AMS
Mathewson et al., 2010	Good (21)	Young adults	76	30.6 (11) [18-55]	33/43	-	Cognitive inhibition	Pictorial Stroop task	Reaction times	-0.245	RSA	6 min.	ECG
Ottaviani et al., 2019	Good (22)	Young adults	50	24.2 (4.0) [19-40]	19/31	22.5 [< 30]	Cognitive flexibility Cognitive inhibition	Rule Shift Card Hayling Sentence Completion Test	Reaction times Reaction times Reaction times Reaction times	-0.42 -0.28 -0.30 -0.29	RMSSD HF RMSSD HF	5 min.	Bodyguard 2
Spangler et al., 2018	Good (20)	Undergraduate students	83	18.9 (1.4)	23/60	22.85 (3.22)	Cognitive inhibition	Stroop task	Accuracy score Reaction time SD of reaction times	0.26 -0.08 -0.11	RMSSD	5 min.	ECG
Stenfors et al., 2016	Good (20)	Working adults	119	48.0 (10.5) [25-66]	94/25	-	Cognitive flexibility	Trail Making Test b	Completion speed	-0.246	RMSSD	5 min.	ECG
							UWM	2-back task	Accuracy score	0.119			
							UWM	2-back task	Reaction time	-0.076			
							Cognitive inhibition	Stroop task	Reaction time	-0.247			
							Cognitive inhibition	Stroop-shifting task	Reaction time	-0.222			
							UWM	Reading span	Span score	0.027			
							UWM	Letter Digit Substitution test	Accuracy score	0.177			
							Cognitive flexibility	Trail Making Test b	Completion speed	0.035			
							UWM	2-back task	Accuracy score	-0.014			
							UWM	2-back task	Reaction time	0.040			
Cognitive inhibition	Stroop task	Reaction time	-0.111	HF (Hz)									
Cognitive inhibition	Stroop-shifting task	Reaction time	-0.085										
UWM	Reading span	Span score	-0.01										

Study	Quality NIH (Strobe)	Population Type	Population			Executive functioning			Pearson' <i>r</i>	HRV recording			
			n	Age*	Men/Women	BMI*	Function	Assessment		Outcomes	Index	Length	Device
Williams, Thayer, & Koenig, 2016	Fair (19)	Undergraduate students	104	19.25 (1.4) [18-25]	56/48	-	UWM	Letter Digit Substitution test	Accuracy score	0.013	HF	5 min.	ECG
							Cognitive inhibition	Modified Flanker task	Accuracy score Reaction time SD of reaction times	0.093 -0.105 -0.313			
Williams et al., 2019	Good (24)	Undergraduate students	79	27.5 (6.5) [20-45]	25/54	25.4 (5.5) [17-44]	Global executive functioning	Delis-Kaplan Executive Function System	Composite score	0.39	HF	5 min.	ECG
							UWM	WAIS: Working Memory Composite	Composite score	0.14			
Xing, Lü, & Wang, 2020	Good (21)	Undergraduate students	132	18 (0.77)	50/82	-	Cognitive inhibition	Go/No-Go	Accuracy score	-0.01	RSA	5 min.	ECG

Note: **N:** sample size, **NIH:** national institutes of health, **SD:** standard deviation, **BMI:** body mass index, **UWM:** updating in working memory, **WAIS:** wechsler adult intelligence scale, **HRV:** heart rate variability, **RMSSD:** root mean square of successive differences, **HF:** high frequency band spectrum of heart rate variability (0.15-0.40 Hz), **RAS:** respiratory sinus arrhythmia, **ECG:** electrocardiogram, **AMS:** ambulatory monitoring system **NA.:** data not available.

* mean, (SD) or [Range].



Fig. 2. Summary bias risk of included articles using the NIH Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies.

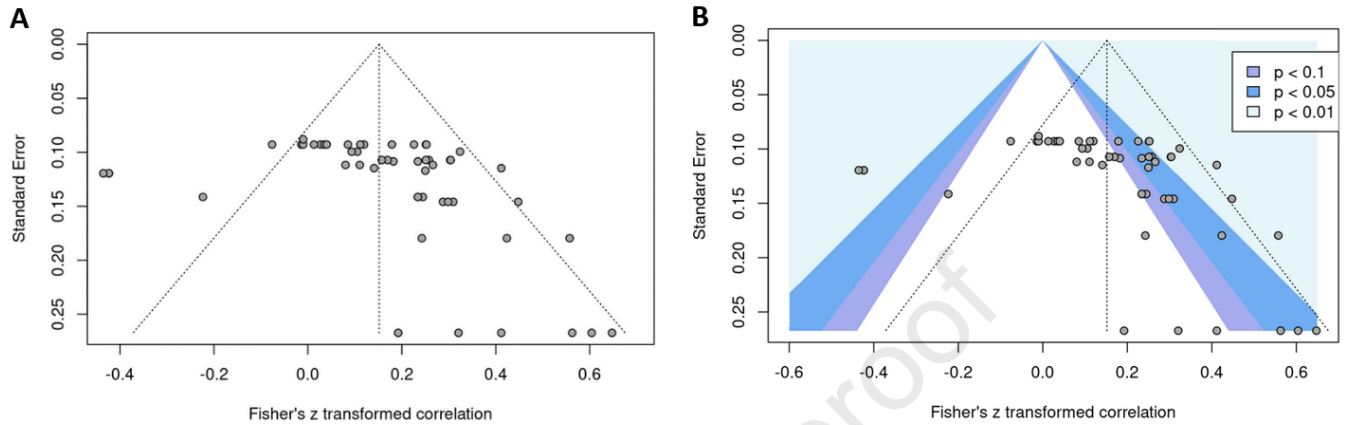


Fig. 3. Funnel plots A and B (contour-enhanced) illustrate the individual effect sizes on the horizontal axis and corresponding standard errors on the vertical axis for the initial model. Visual inspection of plots may indicate possible asymmetry emphasized by 6 studies outside of the idealized funnel-shape centered on the summary effect size (A) including 4 in high significance ($p < 0.01$; B).

Table 2

Sensitivity analysis describing the initial meta-analysis model and the model characteristics after outliers removal (as recommended by Harrer et al., 2021b).

Analysis	k	ES	95 % CI	p	I^2	95 % CI
Initial model	52	0.15	0.09- 0.21	< 0.0001	65 %	53-74
Influential cases removed	46	0.19	0.15- 0.23	< 0.0001	21%	0-46

Note: **CI:** confidence interval, **ES:** summary effect size, **p :** p-value, **I^2 :** Higgins & Thompson's I^2 statistic reflecting the variance in effect size estimates due to true variation among studies. **k :** number of effect sizes included in meta-analysis.

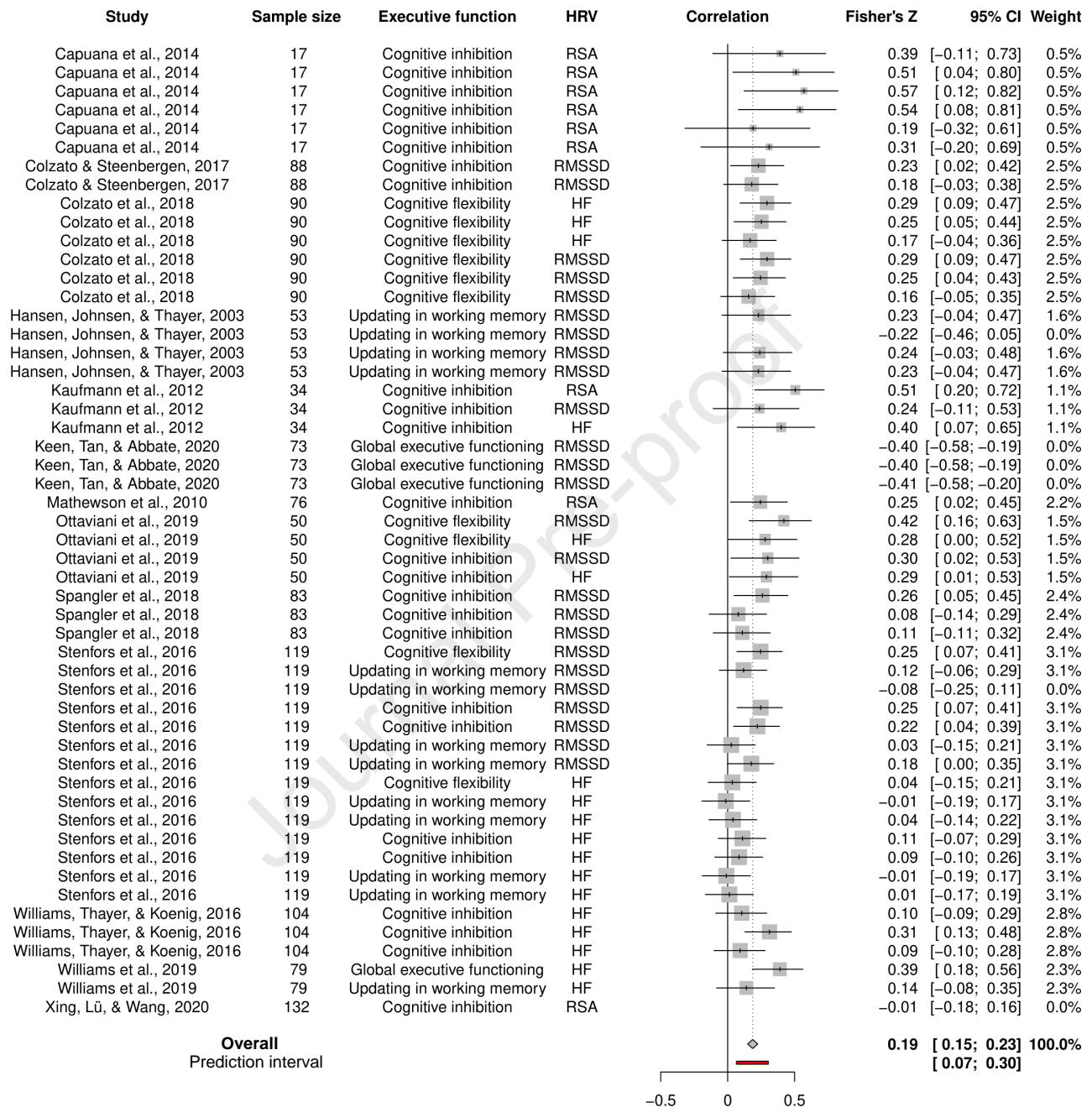


Fig. 4. The relationship between vagally-mediated HRV and executive functioning. Fisher's Z point estimates are depicted by filled grey squares, with square sizes indicating the relative weight of each study's effect size estimates in the analysis with influential cases removed. Each line corresponds to the ES between an HRV index and a cognitive measure. The filled diamond reflects the overall summary effect size (Fisher's Z=0.19, 95% CI 0.15 to 0.23, $p < 0.0001$, $I^2 = 21\%$) and

the red line describes the prediction interval. The absence of a filled grey square means the effect size estimate was excluded from the model following sensitivity analysis.

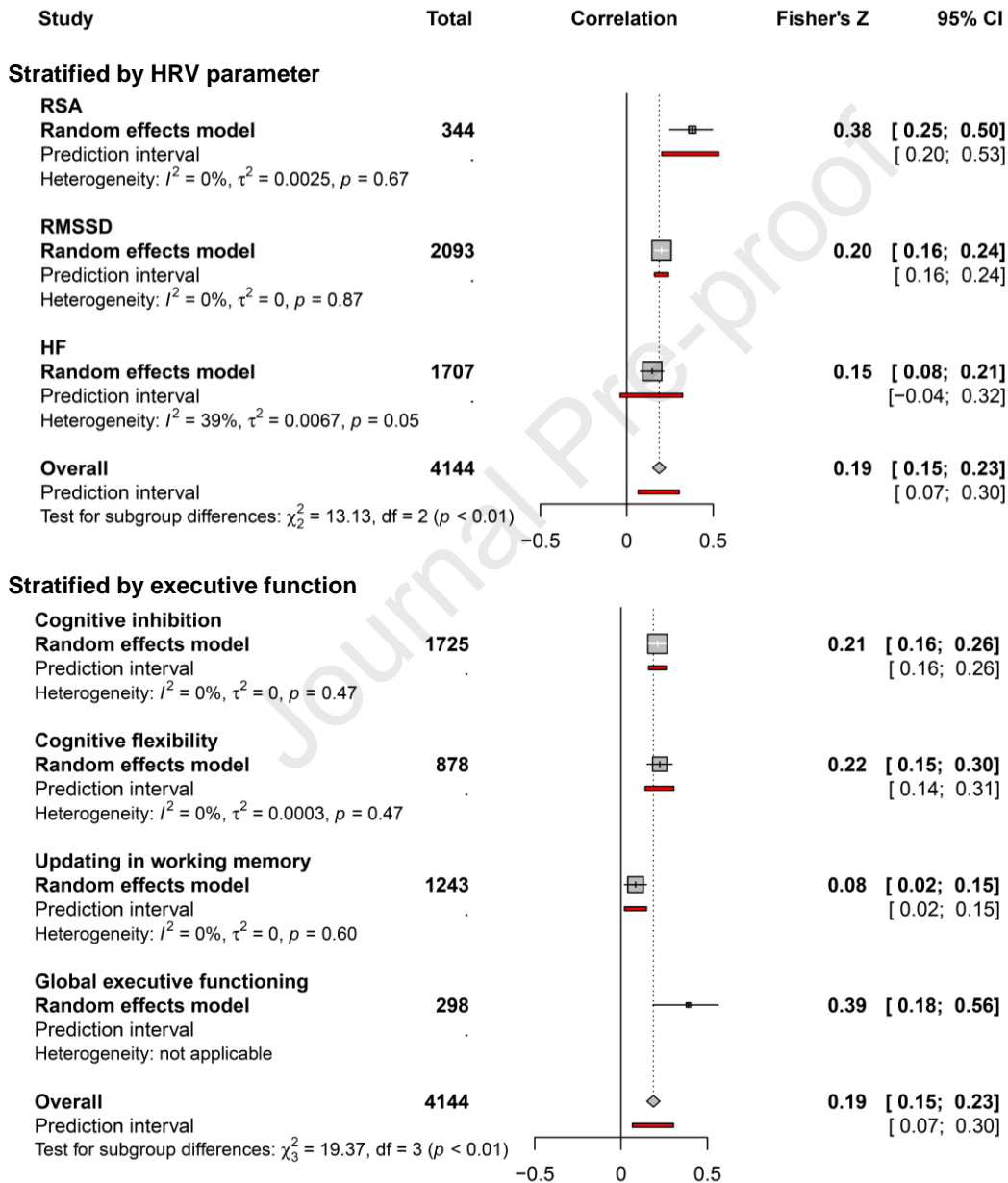


Fig. 5. The relationship between vagally-mediated HRV and executive functioning by HRV parameter and by executive function.

Note: **HF**: high frequency band spectrum of heart rate variability (0.15-0.40 Hz), **HRV**: heart rate variability, **RMSSD**: root mean square of successive differences, **RSA**: respiratory sinus arrhythmia.

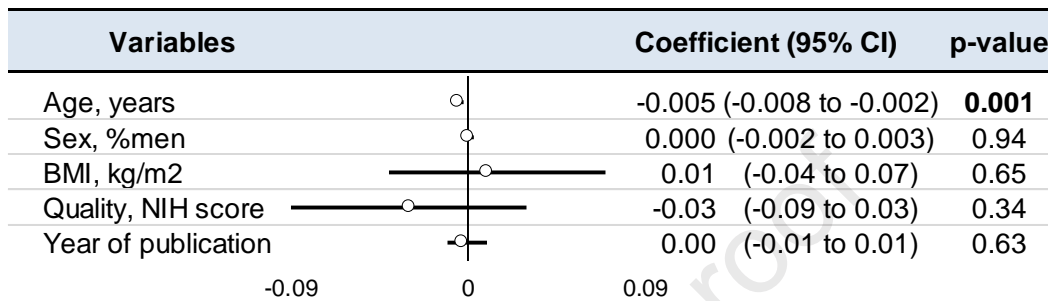


Fig. 6. Visual representation of meta-regression models describing the impact of possible moderators on effect size. The solid black lines in plots represent the standard deviation of the regression coefficient (β ; corresponding to the white circle).

Note: Age and sex distribution were included in the same regression model because they negatively correlated ($r = -0.52$, $p < .001$).