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1 Dissociating facial electromyographic correlates of visual and verbal induced rumination

2 Ladislav Nalborczyk^{1,2,3*}, Sonja Banjac^{1*}, Céline Baeyens⁴, Romain Grandchamp¹, Ernst
3 H. W. Koster², Marcela Perrone-Bertolotti^{1,5}, & Hélène Lœvenbruck¹

4 ¹ Univ. Grenoble Alpes, CNRS, LPNC UMR 5105, F-38000 Grenoble

5 ² Department of Experimental Clinical and Health Psychology, Ghent University

6 ³ GIPSA-lab, CNRS, Univ. Grenoble Alpes, Grenoble INP, 38000, Grenoble, France.

7 ⁴ Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, LIP/PC2S, 38000 Grenoble, France

8 ⁵ Institut Universitaire de France (IUF), France

9 Author Note

10 Correspondence concerning this article should be addressed to Ladislav Nalborczyk,
11 GIPSA-lab, Univ. Grenoble Alpes, Grenoble INP, 11 Rue des Mathématiques, 38400
12 Saint-Martin-d'Hères, France. E-mail: ladislav.nalborczyk@gipsa-lab.fr. *These authors
13 have contributed equally to the work.

Abstract

14

15 Previous research showed that mental rumination, considered as a form of repetitive and
16 negative inner speech, is associated with increased facial muscular activity. However, the
17 relation between these muscular activations and the underlying mental processes is still
18 unclear. In this study, we tried to separate the facial electromyographic correlates of
19 induced rumination related to either i) mechanisms of (inner) speech production or ii)
20 rumination as a state of pondering on negative affects. To this end, we compared two
21 groups of participants submitted to two types of rumination induction (for a total of 85
22 female undergraduate students without excessive depressive symptoms). The first type of
23 induction was designed to specifically induce rumination in a verbal modality whereas the
24 second one was designed to induce rumination in a visual modality. Following the *motor*
25 *simulation view* of inner speech production, we hypothesised that the verbal rumination
26 induction should result in a higher increase of activity in the speech-related muscles as
27 compared to the non-verbal rumination induction. We also hypothesised that relaxation
28 focused on the orofacial area should be more efficient in reducing rumination (when
29 experienced in a verbal modality) than a relaxation focused on a non-orofacial area. Our
30 results do not corroborate these hypotheses, as both rumination inductions resulted in a
31 similar increase of peripheral muscular activity in comparison to baseline levels. Moreover,
32 the two relaxation types were similarly efficient in reducing rumination, whatever the
33 rumination induction. We discuss these results in relation to the inner speech literature
34 and suggest that because rumination is a habitual and automatic form of emotion
35 regulation, it might be a particularly (strongly) internalised and condensed form of inner
36 speech. Pre-registered protocol, preprint, data, as well as reproducible code and figures are
37 available at: <https://osf.io/c9pag/>.

38

Keywords: rumination, repetitive negative thinking, inner speech, covert speech,

39

electromyography, simulation, emulation

40 Dissociating facial electromyographic correlates of visual and verbal induced rumination

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Introduction

42

43 The phenomenon of inner speech has been attracting the attention of the scientific
44 community for a long time. This interest might be explained by the paradox surrounding
45 inner speech: whereas most individuals experience it on a daily basis (but see Hurlburt,
46 2011), inner speech is notably difficult to investigate. However, much can be learned about
47 inner speech by examining its different forms of expression. Among these forms is
48 rumination, which, for several reasons, will be the focus of this paper. First, although
49 rumination is common in the general population (Watkins et al., 2005), it can precede
50 serious mental disorders such as depression, anxiety, eating disorders, or alcohol abuse (for
51 review, see Nolen-Hoeksema et al., 2008). Therefore, understanding the fundamental
52 nature of rumination has important implications for clinical practice. Second, rumination
53 is a repetitive phenomenon which can be induced and sustained for a relatively long period
54 of time, making it potentially easier to capture than more elusive forms of inner speech.
55 With the aim of further exploring the nature of rumination, we present the results of a
56 procedure designed to induce rumination in different modalities (verbal versus visual
57 imagery) to investigate the modality-specific electromyographic correlates of rumination.

58 Defining rumination

59 Rumination can be broadly defined as unconstructive repetitive thinking about past
60 events and current mood states (Martin & Tesser, 1996). One of the most influential
61 frameworks of rumination is the *Response Style Theory* (RST, Nolen-Hoeksema, 1991;
62 Nolen-Hoeksema et al., 2008) that describe rumination as a behavioural pattern that is
63 characterised by perseverative, repetitive, and passive thought. According to the RST,
64 individuals who are experiencing rumination are repetitively focusing on their negative
65 emotional state, on the fact that they are feeling depressed, and on the causes and
66 consequences of their symptoms (Nolen-Hoeksema, 1991). In this framework, rumination is

67 viewed as a type of response to distress or a coping mechanism which involves focusing the
68 attention on oneself and one's current emotional state (Nolen-Hoeksema, 1991). Alloy,
69 Robinson and colleagues (Alloy et al., 2000; Robinson & Alloy, 2003; Smith & Alloy, 2009)
70 also suggested that rumination can also appear following stressful life events, before the
71 start of the depressive mood.

72 Rumination can be operationalised either as a trait, a stable response style of an
73 individual (Nolen-Hoeksema, 1991), or as a state, an ongoing process. In a recent attempt
74 to bridge response styles theories of trait rumination (Nolen-Hoeksema, 1991) and control
75 theory accounts of state rumination (Martin & Tesser, 1996), rumination has been defined
76 as a mental habit (Watkins & Nolen-Hoeksema, 2014). In this framework, self-focused
77 repetitive thoughts (such as rumination) are triggered by goal discrepancies (i.e.,
78 discrepancies between an initial goal and the current state) and can become habitual
79 behavioural responses to certain contextual cues. More precisely, rumination can become
80 habitual through a process of “automatic association between the behavioral response (i.e.,
81 repetitive thinking) and any context that occurs repeatedly with performance of the
82 behavior (e.g., physical location, mood), and in which the repetitive thought is contingent
83 on the stimulus context” (Watkins & Nolen-Hoeksema, 2014).

84 **The nature of ruminative thoughts**

85 Rumination has sometimes been portrayed as a form of *inner speech*
86 (Perrone-Bertolotti et al., 2014) due to its predominantly verbal character (Ehring &
87 Watkins, 2008; Goldwin et al., 2013; Goldwin & Behar, 2012; McLaughlin et al., 2007).
88 However, what inner speech precisely entails is still debated (for a recent review, see
89 Loevenbruck et al., 2018). In the present paper, we examine the *motor simulation view* that
90 considers inner speech production to be the result of a mental simulation of overt speech
91 (Jeannerod, 2006; Postma & Noordanus, 1996). Inner speech is hence conceived as

92 (inhibited) speech motor acts that trigger –via a *simulation* or an *emulation* mechanism–
93 multimodal sensory percepts (Løevenbruck et al., 2018). This perspective entails that the
94 speech motor system should be involved during inner speech production and that we could
95 record a peripheral residual activity in the speech muscles. This hypothesis has been
96 corroborated by several studies using orofacial surface electromyography (EMG) during
97 tasks that involve inner speech production such as silent recitation, verbal mental imagery
98 or problem solving (Jacobson, 1931; Livesay et al., 1996; McGuigan & Dollins, 1989;
99 Sokolov, 1972).

100 In a recent study on the facial EMG correlates of rumination (Nalborczyk et al.,
101 2017), we have demonstrated that induced rumination is accompanied by an increased
102 facial EMG activity concurrent with increased self-reported levels of state rumination, as
103 compared with an initial relaxed state. Furthermore, after a relaxation session focused on
104 the orofacial area, we observed a larger decrease in self-reported state rumination than
105 after non-orofacial –focused on the forearm– relaxation. We interpreted these findings as
106 consistent with the *motor simulation view*. However, we suggested that participants of this
107 study could have been experiencing rumination in other (non-verbal) modalities, such as
108 rumination in visual mental images. Therefore, the present work is in continuity with our
109 previous study, seeking to further investigate the electromyographic correlates of different
110 rumination modalities (i.e., verbal vs. visual imagery).

111 There are indeed findings suggesting that rumination can also be experienced as
112 visual imagery, despite being predominantly experienced in a verbal modality (Goldwin &
113 Behar, 2012; Newby & Moulds, 2012; Pearson et al., 2008). Visual imagery refers to a
114 process during which perceptual information is retrieved from long-term memory, resulting
115 in the experience of “seeing with the mind’s eye” (Ganis et al., 2004). It has been
116 suggested that because rumination is usually past-oriented, it should increase access to
117 (negative) autobiographical memories (Lyubomirsky et al., 1998). Moreover, because

118 autobiographical memories are often experienced as visual images, rumination should
119 likewise include visual features (Pearson et al., 2008).

120 Consistent with this claim, a significant majority (94.7% and more than 70%,
121 respectively) of clinically depressed patients reported that their ruminations combined
122 verbal and sensory elements, among which visual imagery (Newby & Moulds, 2012;
123 Pearson et al., 2008, respectively). When unselected individuals were asked about the
124 quality of their rumination directly while ruminating, 60.53% of them said they had been
125 experiencing verbal thoughts and 35.92% mental images (McLaughlin et al., 2007). Studies
126 also showed that a considerable number of people experience depressive rumination in a
127 visual form (Lawrence et al., 2018) and that depressive thoughts involve more images than
128 anxious thoughts in a non-clinical sample (Papageorgiou & Wells, 1999). Overall, the
129 existing literature indicates that rumination can have visual features, despite being
130 predominantly verbal.

131 **Manipulation of rumination modality**

132 Although several studies explored how much ongoing rumination was verbal or visual
133 (e.g., Goldwin & Behar, 2012; McLaughlin et al., 2007), only a few studies experimentally
134 manipulated the *modality* of rumination. Some of the few studies specifically manipulating
135 verbal and visual rumination were carried out by Zoccola and colleagues (Woody et al.,
136 2015; Zoccola et al., 2014). The verbal or visual form of rumination was induced by playing
137 audio tapes that directed participants' thoughts. Prompts were similar in both conditions,
138 differing only in the verbal/visual instruction ("Recall the speech task using words, phrases,
139 and sentences." vs. "Recall the speech task using pictures and images."). Participants were
140 subsequently asked to estimate the proportion of verbal thoughts and mental visual images.
141 Although not directly focused on rumination, the task developed by Holmes et al. (2008) is
142 inspiring for exploring rumination in different modalities. These authors aimed to compare

143 verbal and imagery processing in terms of their differential effects on emotion. They
144 noticed that previous procedures provided verbal descriptions of the events that needed to
145 be processed verbally or visually. The authors argued that with such descriptions, the
146 imagery condition has an additional processing mode in comparison to the verbal condition.
147 To make the verbal and imagery conditions more comparable in terms of processing load,
148 they combined pictorial and verbal cues and asked participants to integrate them using
149 either a sentence or an image.

150 Finally, it should be noted that in none of the studies in which thinking modality was
151 manipulated, did the participants solely use one type of thought. For instance, the
152 participants in the verbal group of Zoccola et al. (2014) also reported a certain level of
153 mental imagery. This is in line with studies showing that rumination includes both verbal
154 and visual components (e.g., Goldwin & Behar, 2012; McLaughlin et al., 2007), implying
155 that it is not exclusively experienced in one modality. These results are substantiated by
156 recent findings showing that participants generated visual images both in cases where they
157 were told to visualise or to think verbally, while they generated robust verbal
158 representations only when asked to think verbally (Amit et al., 2017). Moreover, Amit et
159 al. (2017) suggested that individuals may have better control over inner speech than over
160 visual thought. Therefore, we will focus on the relative use of a specific mode of thought
161 rather than trying to induce completely verbal or visual thought.

162 **The present study**

163 There is a need for studies that induce verbal or visual rumination in order to inspect
164 whether and how the experience of rumination in these two modalities differ (Lawrence et
165 al., 2018). Furthermore, there has only been one set of studies, to the best of our
166 knowledge, that has employed a protocol for specifically inducing verbal or visual
167 rumination (Woody et al., 2015; Zoccola et al., 2014). In addition, there were a few

168 shortcomings in this protocol, some of which were highlighted by the authors, such as the
169 stress induction component. To tackle these issues, we extended the study presented in
170 Nalborczyk et al. (2017) by inducing rumination in distinct modalities to compare their
171 electromyographic correlates.

172 As previously (Nalborczyk et al., 2017), we followed two steps in our protocol. First,
173 either verbal or visual rumination was induced in participants by putting them in a stressful
174 situation and subsequently asking them to think either verbally or visually about the
175 causes, consequences of their feelings during that situation. Based on the task developed by
176 Holmes et al. (2008), and following their recommendation to balance processing load in
177 both thinking modes, instructions were presented by combining pictorial and verbal cues.
178 During this period, we tracked changes in the EMG activity of several facial muscles and
179 monitored self-reported levels of state rumination. Second, we compared the effects of two
180 types of relaxation (orofacial vs. arm) in relation to the modality of ruminative thoughts,
181 on both the EMG amplitude and the self-reported levels of state rumination.

182 Several hypotheses were drawn based on the existing literature. First, we expected
183 participants in the verbal rumination condition to report a larger proportion of verbal
184 content in their inner experience and a lesser amount of visual content (in comparison to
185 participants in the visual rumination group). Second, with respect to peripheral muscular
186 activity, we expected the activity in the speech muscles to increase by a greater amount in
187 the verbal rumination condition, whereas changes in non-speech muscles should occur
188 similarly in both conditions, since both conditions are expected to cause negative emotions
189 to a similar extent. Moreover, control forearm muscle activity should not vary distinctively
190 between conditions. Third, regarding the different types of relaxation, we hypothesised
191 that both orofacial and arm relaxation should cause a slight decrease of state rumination in
192 the verbal condition. Nevertheless, we expected a stronger decrease in the orofacial
193 relaxation condition as compared to the forearm relaxation.

Methods

194

195 In the *Methods* and *Data analysis* sections, we report how we determined our sample
196 size, all data exclusions, all manipulations, and all measures in the study (Simmons et al.,
197 2012). A pre-registered version of our protocol can be found online: <https://osf.io/c9pag/>.

198 Participants

199 Our sample included 85 female participants, ranging in age from 18 to 31 years ($M =$
200 19.87 , $SD = 2.02$). We chose to include only female participants in the present study, for
201 the following two reasons. First, women have been found to engage in rumination more
202 than men (Johnson & Whisman, 2013). Second, in comparison with men, women have
203 greater visual imagery abilities and report more vivid mental visual images (as reviewed in
204 Lawrence et al., 2018). All participants attended undergraduate Psychology programs at
205 Univ. Grenoble Alpes and were native speakers of French. They reported no history of
206 psychiatric or neurological disorders, speech disorders or hearing deficits. Another inclusion
207 criterion was that participants had no to limited depressive symptoms. This was tested at
208 the beginning of the experiment using the Center for Epidemiologic Studies – Depression
209 scale (CES-D, Radloff, 1977). Those participants whose scores overstepped the threshold
210 did not proceed to the main part of the experiment ($N = 16$). Instead, they were debriefed
211 and received information about places they could turn to for counselling.

212 Participants were recruited through the university website. They were told that the
213 goal of the study was to test a French adaptation of a novel intelligence test and were,
214 therefore, blind to the actual goal of the study. Participants received course credits for
215 their participation and were fully debriefed at the end of the experiment. Written consent
216 was obtained from each participant and the study received an approval from the local
217 ethical committee (CERNI, Amendement-2018-02-06-23, Avis-2015-03-03-61).

218 As described in the preregistration form, we used sequential testing to determine the
219 appropriate sample size. More precisely, we recruited participants until reaching either a
220 predetermined level of precision (this procedure is described in Kruschke, 2015) or the end
221 of the period of time allocated to this experiment (fixed to eight weeks). We first
222 determined a region of practical equivalence (ROPE) and a target precision level on the
223 main effect of interest (i.e., the interaction between the effect of time (baseline versus
224 post-induction, within-subject) and group (verbal rumination versus visual rumination
225 induction, between-subject design), on the EMG amplitude of the OOI muscle). We
226 recruited participants until the 95% credible interval (the Bayesian analogue of a confidence
227 interval) around the parameter of interest was at least 0.8 times narrower than the ROPE.
228 The ROPE can be defined as the region comprising the effect sizes that we consider as “null
229 effects” (alternatively, it defines the minimum effect size of interest). We defined the ROPE
230 as $[-0.1, 0.1]$ on the scale of the normalised and baseline-standardised EMG amplitude.
231 This ROPE has been defined to correspond to a “null effect” based on previous EMG data
232 we have collected on control muscles (forearm). Then, we defined the target precision as
233 0.8 times the width of the ROPE, that is: $0.8 \times 0.2 = 0.16$. We did not reach this
234 threshold within the allocated time. Thus, we ran the study for the full eight weeks (details
235 on the evolution of the estimation precision can be found in the supplementary materials).

236 **Material and EMG setup**

237 The experimental procedure was developed using the OpenSesame software (Mathôt
238 et al., 2012) and stimuli were displayed on a DELL computer screen of size 1280px*720px.
239 Trigno™ Mini wireless sensors (Delsys Inc.) were used for the detection of the surface
240 EMG signals. These sensors consist of a bigger and a smaller box. The smaller box
241 contains two 5x1mm parallel electrode bars with 10mm between them that record bipolar
242 muscle activation. For facial EMG, the small box with electrodes was attached to the face

243 and the bigger box was usually placed on the side of the neck. Concerning the forearm
244 EMG, both boxes were placed on the forearm. Both boxes were attached by double-sided
245 adhesive tape. Before setting the sensors, the skin was cleaned by Nuprep scrubbing gel
246 and by alcohol wipes. Signal acquisition and synchronisation was done using the PowerLab
247 16/35 (ADInstrument, PL3516) device with a sampling rate of 1000 Hz. In addition to
248 EMG measurements, the audio signal was simultaneously recorded using a C1000S AKG
249 microphone which was placed 20-30 cm away from the participant. The audio signal was
250 amplified using a Berhringer Tube Ultragain MIC100 amplifier. It was synchronised with
251 the EMG signals using trigger signals. The experiment was video-monitored using a Sony
252 HDR-CX240E camera. These recordings were taken in order to track any vocal or
253 behavioural artefacts during periods of interest (i.e., baseline, rumination and relaxation).
254 Labchart 8 software (ADInstrument, MLU60/8) was used for EMG and audio data
255 collecting and processing.

256 Our exploration focused on the muscles that have already been found to be activated
257 during covert or overt speech (e.g., Fromkin, 1966; Kennedy & Abbs, 1979; Laurent et al.,
258 2016; Lieshout Pascal H. H. M. van et al., 1993; Maier-Hein et al., 2005; Schultz & Wand,
259 2010). With surface EMG, it is difficult to precisely relate a given skin position to a
260 specific muscle. However, as authors often refer to the facial positions as muscle positions,
261 we will follow this tradition for clarity. Because of their involvement in speech production,
262 bipolar surface EMG electrodes were positioned on the orbicularis oris inferior (OOI), the
263 zygomaticus major (ZYG), and on the neck region, potentially reflecting the activity of
264 platysma and tongue muscles (NCK). It should be mentioned that in addition to their
265 contribution to lip movement and configuration during speech, OOI and ZYG have also
266 been associated with negative and positive valence emotions, respectively. Given that their
267 involvement in emotion is of opposite direction, using both sites may help to disentangle
268 between emotion- and speech-related activation. In addition, electrodes were also placed on
269 the frontalis (FRO) as a non-speech but negative-emotion-related muscle. The corrugator

270 supercillii muscle, often cited as a negative-emotion-related muscle (Tan et al., 2012), was
271 not used because it is associated with eyebrow movements, which have been shown to
272 accompany speech production (Bolinger, 1986; Krahmer & Swerts, 2004). Finally, we
273 positioned a sensor on the flexor carpi radialis (FCR) to control for general (whole body)
274 muscle contraction (see the supplementary materials for a depiction of the position of the
275 sensors).

276 Speech-related sensors were positioned on the right side of the face whereas the
277 emotion-related (forehead) sensor was positioned on the left side of participants' faces,
278 following studies that found larger movements of the right side of the mouth during speech
279 production (Nicholls & Searle, 2006), and more emotional expression on the left side of the
280 face (Nicholls et al., 2004). Since participants were asked to use a mouse to provide
281 answers, the forearm sensor was positioned on the non-dominant forearm (that participants
282 did not use to provide the answer).

283 Procedure

284 Participants were randomly allocated to one of four groups, varying by the modality
285 in which they were asked to ruminate in (*verbal* vs. *visual*) and the type of relaxation they
286 were listening to (*orofacial* relaxation vs. *arm* relaxation). As a result, there were four
287 groups in the experiment: *verbal – orofacial*, *verbal – arm*, *visual – orofacial*, and *visual –*
288 *arm*. As reported in Table 1 of the supplementary materials, the groups did not differ
289 significantly in terms of age or trait measures.

290 **Trait questionnaires.** After filling the consent form, participants were asked to
291 complete the CES-D (Radloff, 1977). Participants also filled out the short version of the
292 Ruminative Response Scale (RRS, Treynor et al., 2003), adapted and validated in French
293 (Douilliez, Guimpel, Baeyens, & Philippot, in preparation). These questionnaires were

294 filled in paper format. Once it was determined that they could participate in the study
295 (i.e., that they did not exceed the threshold for depressive symptoms on the CES-D),
296 participants were equipped with the EMG sensors.

297 **State questionnaires.** Subsequently, a calibration was carried out, making sure
298 that the sensors on each muscle were suitably detecting signals. Participants were then
299 explained the Visual Analogue Scales (VASs) that were used to obtain various self reports
300 throughout the experiment. Specifically, we explained what we meant by: *At this moment,*
301 *my thoughts are presented in the form of words (VAS Verbal)*, and *At this moment, my*
302 *thoughts are presented in the form of visual mental images (VAS Visual)*. To assess the
303 level of state rumination, we used a French translation of the Brief State Rumination
304 Inventory (BSRI, Marchetti et al., 2018), composed of eight items also presented as VASs.
305 State rumination is then assessed using the sum of the scores on these eight items (as
306 suggested by Marchetti et al., 2018). From that point, the rest of the stimuli were
307 presented on the computer screen and speakers, and the experimenter (blind to the
308 condition) did not interact with the participants anymore.

309 **Baseline measurements.** Afterwards, participants listened to a guided relaxation
310 (not focused on any specific muscle). The purpose of this relaxation was to minimise
311 inter-individual variability of the initial mood states and to help participants to relax and
312 get used to wearing the EMG sensors. The recording comprised 240 seconds of guided
313 relaxation, then a pause was made during which participants were told to continue relaxing
314 and the baseline EMG measurements were recorded, after which the guided relaxation
315 continued for another 30 seconds. Following this, baseline level of state rumination, verbal
316 and visual level of thoughts were registered using the VASs.

317 **Imagery training (verbal and visual modes).** Next, participants went through
318 a “lemon training” based on the task proposed by Holmes et al. (2008). The objective of
319 this training was to show the participants precisely what was meant by *thinking in words*

320 or *thinking in pictures*. The participants in the *verbal* group were asked to covertly
321 generate an appropriate sentence combining an image (e.g., a lemon) and a caption word
322 (e.g., “cut”), whereas participants in the *visual* group were asked to imagine a picture
323 combining the image and the caption word. There were two trials. After each trial,
324 participants rated how clear (how vivid) their sentence or image was, following which they
325 had to say or describe it out loud. This served as a verification that participants did the
326 task and that they understood it.

327 **Stress induction.** Afterwards, participants took the intelligence test. We used a
328 balanced number of verbal and visual problems to be solved so as not to bias thinking
329 mode. The test comprised 18 verbal and 18 spatial intelligence questions. It was designed
330 in a way that most (13/18) questions were very difficult while also containing certain
331 (5/18) items that were relatively easy, in order not to demotivate the participants.
332 Participants were instructed to provide their answer within 30 seconds. The number of
333 questions was selected so that even if participants replied very fast, they still encountered
334 around 15 minutes of this frustrating situation. This manipulation has already been shown
335 successful in inducing a negative mood (Nalborczyk et al., 2017).

336 **Rumination induction.** When the test was done, participants were asked to think
337 about the causes, meanings and consequences of their performance during the test and of
338 their current feelings, while their IQ score was being calculated. The participants in the
339 *verbal* group were asked to do this *with their inner voice* and the participants in the *visual*
340 group *using mental visual images*. Following Holmes et al. (2008)’s recommendation for
341 balanced processing load, the instructions were presented in written format together with
342 an image showing a person thinking in words (in the *verbal* group) or in pictures (in the
343 *visual* group). When ready, participants pressed the key and a loading sign showed on their
344 screen which lasted for 5 minutes during which participants were expected to ruminate
345 either using inner speech or mental images. When this period was done, participants were

346 again presented with the VASs.

347 **Muscle-specific relaxation.** Finally, participants listened again to a guided
348 relaxation, only this time there were two types of relaxation. One half of the verbal group
349 and one half of the visual group were assigned to an *orofacial relaxation* group and they
350 listened to the relaxation that was focused on the mouth. The other two halves of both
351 groups were randomly assigned to an *arm relaxation* group and they listened to the
352 relaxation concentrated on the arm. Both relaxations had a similar structure with around
353 270 seconds of guidance, 60 seconds of pause during which the EMG measurements were
354 performed and 25 seconds of relaxation closure. At the very end, participants were asked to
355 write down what they thought was the goal of the experiment and what they were thinking
356 during the score calculation (i.e., the rumination period). The first question served to
357 assess a potential compliance bias since, due to the goal of the experiment (i.e.,
358 manipulation of the rumination modality), we could not make participants completely
359 blind to the task. The second question served again to check how well participants followed
360 the instruction. At the end of the experiment, participants were given an exhaustive
361 debriefing explaining the goals of the research.

362 **EMG signal processing**

363 Data were collected using Labchart8 and were subsequently exported to Matlab for
364 signal processing (www.mathworks.fr, Matlab r2015a, version 8.5.0.197613). First, a 50Hz
365 frequency comb filter was applied to eliminate power noise. Then, in keeping with the
366 recommendation for facial EMG studies (De Luca et al., 2010), a 20 Hz – 450 Hz bandpass
367 filter was applied, in order to focus on the facial EMG frequency band. The EMG signal
368 was centred to its mean and cut with respect to the three periods of interest (i.e., baseline,
369 rumination and relaxation), all of which were divided into 5s blocks. These data were then
370 exported to R version 3.5.0 (R Core Team, 2018), where the mean of the absolute signal

371 was calculated for each 5s block. Thus, a score for each muscle, in each period, for each
372 participant was calculated. Absolute EMG values are not meaningful as muscle activation
373 is never null, even in resting conditions, due in part to physiological noise. In addition,
374 there are inter-individual variations in the amount of EMG amplitude in the baseline. To
375 normalise for baseline amplitude across participants, we thus subtracted the EMG
376 amplitude of the baseline to the two periods of interest (i.e., after rumination and after
377 relaxation) and divided it by the variability of the signal at baseline for each muscle and
378 each participant.

379 Although participants were given the instruction to remain still during inner speech
380 production or listening, small facial movements (such as swallowing movements) sometimes
381 occurred. Such periods were excluded from the final sample of EMG signals. To remove
382 these signals, we visually inspected audio and EMG signals recorded during each trial (a
383 trial corresponds to a five-second-long period of EMG signal). For the trials during which
384 unwanted activity appeared, we excluded the entire trial (i.e., we did not include this trial
385 in the final analysis, for any of the recorded muscles). This inspection was realised
386 independently by two judges (LN and SB). The agreement rate between the two judges was
387 of 87.35% (with a good Cohen's κ of approximately 0.74). Subsequently, the two judges
388 met to reach a consensus about the ambiguous trials (i.e., the trials that were rejected by
389 only one of the two judges) and to decide whether the trial should be kept or excluded
390 (this concerned 967 trials). The overall procedure led to an average (averaged over
391 participants) rejection rate of 58.99% (SD = 21.89).

392 **Data analysis**

393 Statistical analyses were conducted using R version 3.5.0 (R Core Team, 2018), and
394 are reported with the `papaja` (Aust & Barth, 2018) and `knitr` (Xie, 2018) packages.

395 To model EMG amplitude variations in response to the rumination induction, we
396 fitted a Bayesian multivariate regression model with the standardised EMG amplitude as
397 an outcome and *Group* as a categorical predictor (contrast-coded). We used the same
398 strategy for modelling the interaction effect between the type of induction and the type of
399 rumination induction.¹ These analyses were conducted using the **brms** package (Bürkner,
400 2018), an R implementation of Bayesian multilevel models that employs the probabilistic
401 programming language **Stan** (Carpenter et al., 2017).

402 **Stan** implements gradient-based Markov Chain Monte Carlo (MCMC) algorithms,
403 which allow yielding posterior distributions that are straightforward to use for interval
404 estimation around all parameters. Four chains were run for each model, including each
405 10.000 iterations and a warmup of 2.000 iterations. Posterior convergence was assessed
406 examining autocorrelation and trace plots, as well as the Gelman-Rubin statistic. Constant
407 effects estimates were summarised via their posterior mean and 95% credible interval (CrI),
408 where a credible interval interval can be considered as the Bayesian analogue of a classical
409 confidence interval, except that it can be interpreted in a probabilistic way (contrary to
410 confidence intervals). When applicable, we also report Bayes factors (BFs) computed using
411 the Savage-Dickey method.² These BFs can be interpreted as updating factors, from prior
412 knowledge (what we knew before seeing the data) to posterior knowledge (what we know
413 after seeing the data).

¹ An introduction to Bayesian statistical modelling is outside the scope of the current paper but the interested reader is referred to Nalborczyk et al. (2019), for an introduction to Bayesian multilevel modelling using the **brms** package.

² This method simply consists in taking the ratio of the posterior density at the point of interest divided by the prior density at that point (Wagenmakers et al., 2010).

Results

414

415 The results section is divided into two sections investigating the effects of i) the type
416 of rumination induction and ii) the interaction effect between the type of rumination
417 induction and the type of relaxation. Each section is further divided into two subsections
418 reporting either confirmatory (preregistered) or exploratory (non-preregistered) analyses.

419 **Effects of the rumination induction and rumination modality**

420 **Descriptive statistics and figures.** We represent the standardised EMG
421 amplitude during the rumination period for each facial muscle in Figure 1. This figure
422 reveals that the average standardised EMG amplitude was higher than baseline after the
423 rumination induction for both the OOI and FRO muscles, while it was at the baseline level
424 (on average) for the ZYG and lower than baseline for the NCK. Overall, this figure does
425 not show any group (modality-specific) differences (detailed numerical descriptive statistics
426 are reported in the supplementary materials).

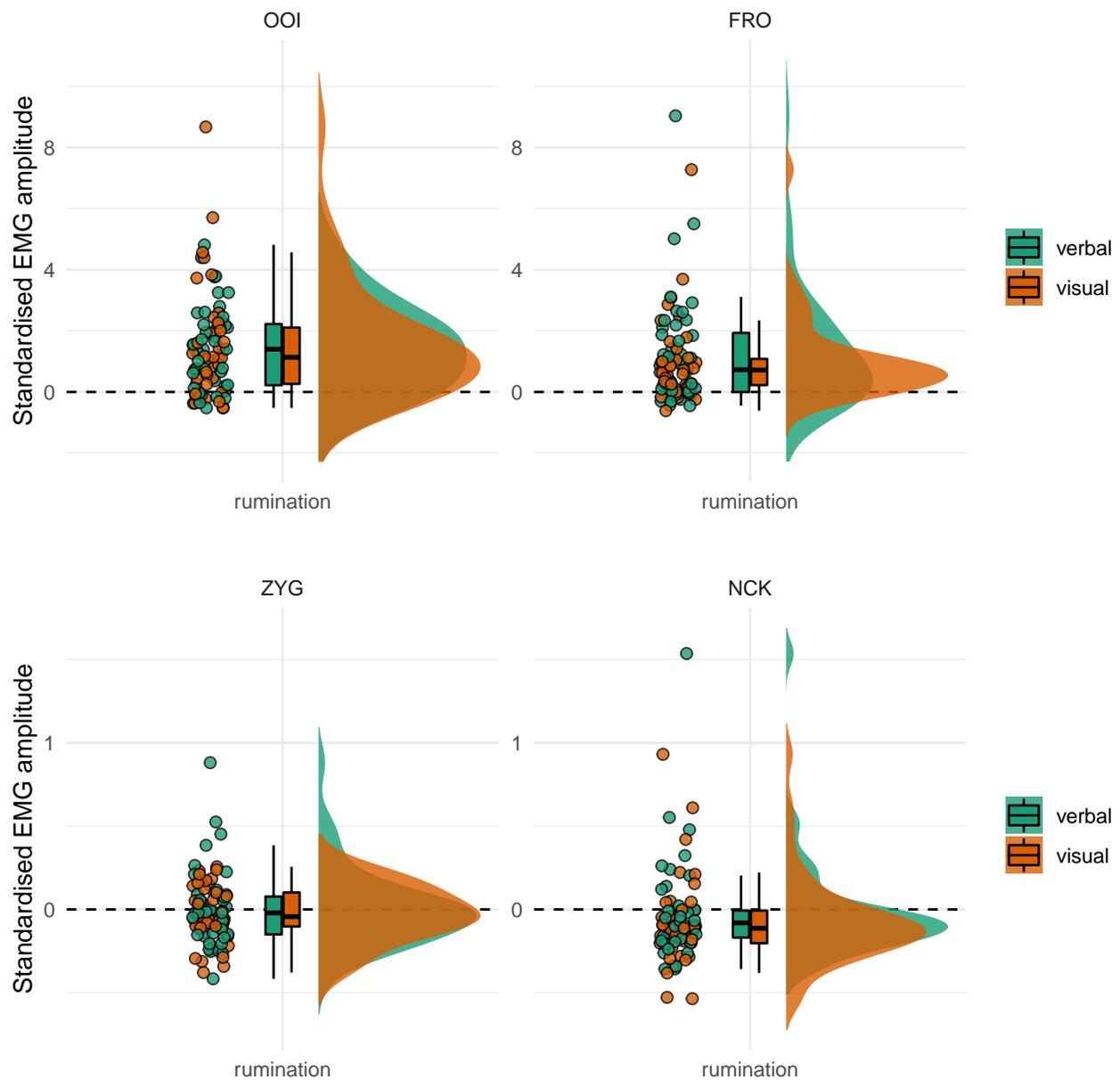


Figure 1. Standardised EMG amplitude during the rumination period. The coloured dots represent the mean standardised EMG amplitude by participant and by type of induction. The boxplot represents the median as well as the first and third quartiles. Note: the y-axis differs between the two rows.

427

Confirmatory (preregistered) analyses. In accordance with the preregistered

428

analysis plan, we then fitted a multivariate Gaussian model to estimate the effects of the

429 rumination induction and the difference between the two types of rumination induction.
 430 Estimations from this model are reported in Table 1.

Table 1

Estimates from the multivariate Gaussian model.

Response	Term	Estimate	SE	Lower	Upper	Rhat	BF01
OOI	Intercept	1.084	0.181	0.726	1.438	1.000	4.800×10^{-12}
OOI	group	0.204	0.341	-0.467	0.866	1.000	2.489
ZYG	Intercept	-0.049	0.033	-0.114	0.015	1.000	10.027
ZYG	group	0.060	0.065	-0.069	0.188	1.000	9.921
FRO	Intercept	1.436	0.177	1.087	1.783	1.000	5.096×10^{-17}
FRO	group	-0.066	0.339	-0.728	0.599	1.000	2.878
NEK	Intercept	-0.012	0.023	-0.057	0.033	1.000	39.52
NEK	group	0.026	0.045	-0.062	0.114	1.000	18.608
FCR	Intercept	-0.047	0.036	-0.119	0.024	1.000	11.977
FCR	group	0.109	0.072	-0.034	0.249	1.000	4.505

Note. For each muscle (response), the first line represents the estimated average amplitude after the rumination induction and its standard error (SE). The second line represents the estimated average difference between the two types of induction (verbal vs. visual). The 'Lower' and 'Upper' columns contain the lower and upper bounds of the 95% CrI, whereas the 'Rhat' column reports the Gelman-Rubin statistic. The last column reports the BF in favour of the null hypothesis.

431 This analysis revealed that the average EMG amplitude of both the OOI and the
 432 FRO muscles was estimated to be higher than baseline (the standardised score was above
 433 zero) after rumination induction. However, it was not the case for the ZYG, NCK, and
 434 FCR muscles. We did not observe the hypothesised difference according to the type of

435 induction on the OOI ($\beta = 0.204$, 95% CrI [-0.467, 0.866], $BF_{01} = 2.489$) nor on the FRO
 436 ($\beta = -0.066$, 95% CrI [-0.728, 0.599], $BF_{01} = 2.878$).

437 However, before proceeding further with the interpretation of the results, it is
 438 essential to check the validity of this first model. A useful diagnostic of the model's
 439 predictive abilities is known as *posterior predictive checking* (PPC) and consists in
 440 comparing observed data to data simulated from the posterior distribution (e.g., Gelman et
 441 al., 2013). Results from this procedure are represented in Figure 2.

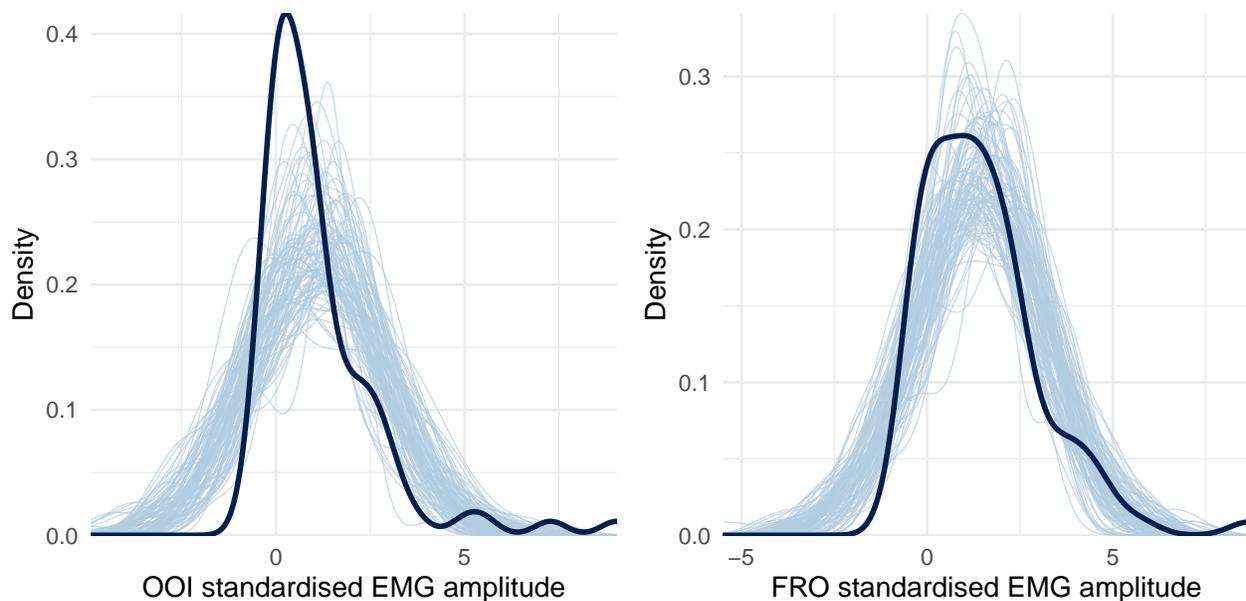


Figure 2. Posterior predictive checking for the first model concerning the OOI and FRO muscles. The dark blue line represents the distribution of the raw data while light blue lines are dataset generated from the posterior distribution.

442 **Exploratory analyses.** Figure 2 reveals that this first model fails to generate data
 443 that look like the data we have collected. More precisely, the data we have collected look
 444 highly right-skewed, especially concerning the OOI. As such, modelling the (conditional)
 445 mean of the standardised EMG amplitude is highly sensitive to influential observations,
 446 and might not be the best index to evaluate the effects of the type of rumination induction.

447 To improve on this first model, we then assume in the following a Skew-Normal
448 distribution for the response. The Skew-Normal distribution is a generalisation of the
449 Gaussian distribution with three parameters ξ (ξ), ω (ω), and α (α) for location,
450 scale, and shape (skewness), respectively. Another limitation of the previous model is that
451 it allocated the same weight to every participant. However, for some participants, we had
452 to remove as much as 91.67% of their data (during the manual artefact removal step).
453 Accordingly, these participants should weigh less in the estimation of the overall effect. In
454 the following models, we weigh the importance of each participant by 1 minus the
455 proportion of signal that was rejected for this participant.³ Estimations from this model
456 are reported in Table 2.

³ Technically, what is weighed is the contribution of the observation to the *likelihood* function.

Table 2

Estimates from the multivariate (weighted) Skew-Normal model.

Response	Term	Estimate	SE	Lower	Upper	Rhat	BF01
OOI	Intercept	1.240	0.188	0.892	1.631	1.000	9.712×10^{-17}
OOI	group	-0.069	0.278	-0.607	0.491	1.000	3.553
ZYG	Intercept	-0.046	0.040	-0.121	0.037	1.000	11.732
ZYG	group	0.080	0.069	-0.058	0.215	1.000	7.153
FRO	Intercept	1.502	0.218	1.102	1.963	1.000	1.740×10^{-16}
FRO	group	-0.003	0.333	-0.660	0.673	1.000	3.156
NEK	Intercept	-0.013	0.033	-0.074	0.053	1.000	28.515
NEK	group	0.003	0.059	-0.112	0.119	1.000	16.807
FCR	Intercept	-0.021	0.044	-0.104	0.070	1.000	19.064
FCR	group	0.144	0.083	-0.018	0.308	1.000	2.64

Note. For each muscle (response), the first line represents the estimated average amplitude after the rumination induction and its standard error (SE). The second line represents the estimated average difference between the two types of induction (verbal vs. visual). The 'Lower' and 'Upper' columns contain the lower and upper bounds of the 95% CrI, whereas the 'Rhat' column reports the Gelman-Rubin statistic. The last column reports the BF in favour of the null hypothesis.

457 This analysis revealed that the average EMG amplitude of both the OOI and the
 458 FRO muscles was estimated to be higher than baseline (the standardised score was above
 459 zero) after rumination induction. However, it was not the case for the ZYG, NCK and
 460 FCR muscles. We did not observe the hypothesised difference according to the type of
 461 induction on the OOI ($\beta = -0.069$, 95% CrI [-0.607, 0.491], $BF_{01} = 3.553$) nor on the FRO
 462 ($\beta = -0.003$, 95% CrI [-0.66, 0.673], $BF_{01} = 3.156$). The posterior predictive checks for this

463 model are presented in Figure 3 and indicate that this model seems to better accommodate
 464 the collected data.

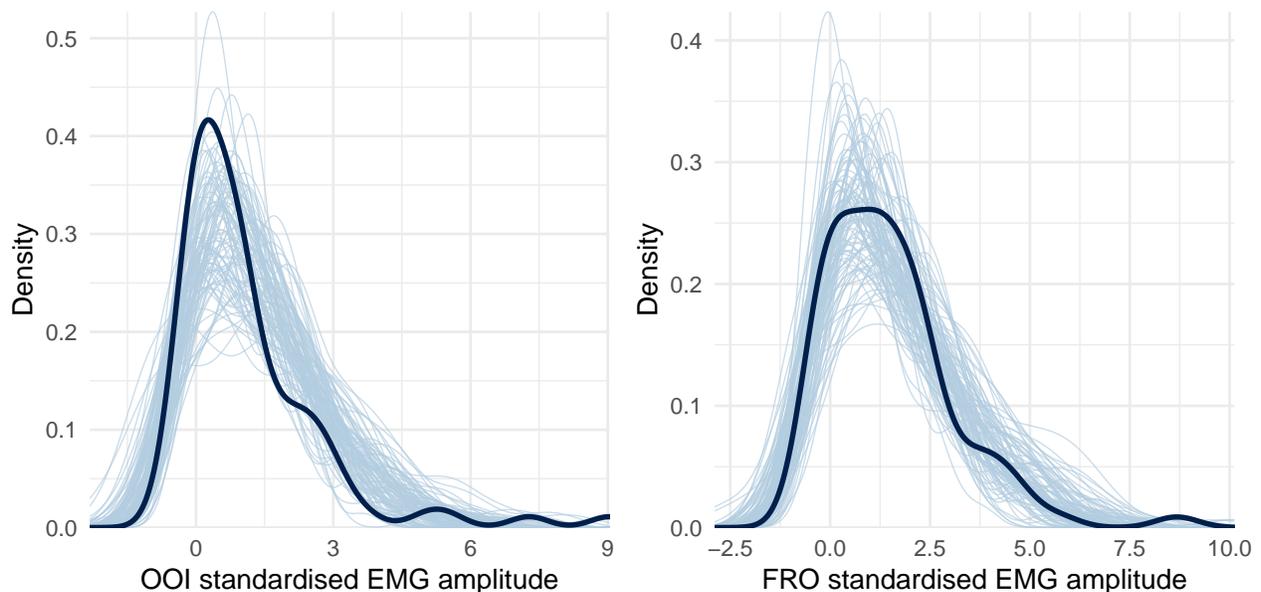


Figure 3. Posterior predictive checking for the Skew-Normal model concerning the OOI and FRO muscles. The dark blue line represents the distribution of the raw data while light blue lines are dataset generated from the posterior distribution.

465 ***Cluster analyses.***

466 The results of the previous analyses do not corroborate the hypothesis according to
 467 which the average EMG amplitude recorded over the speech muscles should be higher in
 468 the group that underwent the verbal rumination induction, as compared to the non-verbal
 469 rumination induction. However, we might wonder whether the rumination induction was
 470 actually efficient in inducing different modalities of ruminative thoughts. To answer this
 471 question, we first report the average self-reported levels of either verbal or visual thoughts
 472 during the rumination period in Table 3.

Table 3

Mean and SE of self-reported levels of either verbal or visual thoughts at the end of the rumination period.

Group	Verbal VAS	Visual VAS	Sample size
verbal	87.11 (2.84)	31.58 (4.39)	44
visual	83.29 (4.03)	30.68 (4.47)	41

473 Considering that both groups showed a similar ratio of verbal/non-verbal thoughts
474 (cf. Table 3), we used these self-reports to a posteriori define groups of participants that
475 reported more verbal (or non-verbal) ruminations. To this end, we used a cluster analysis
476 (2D k-means) to define two groups (clusters) in the space of the two VASs that had been
477 used to assess the amount of verbal and non-verbal thoughts during the rumination period
478 (see Figure 4).

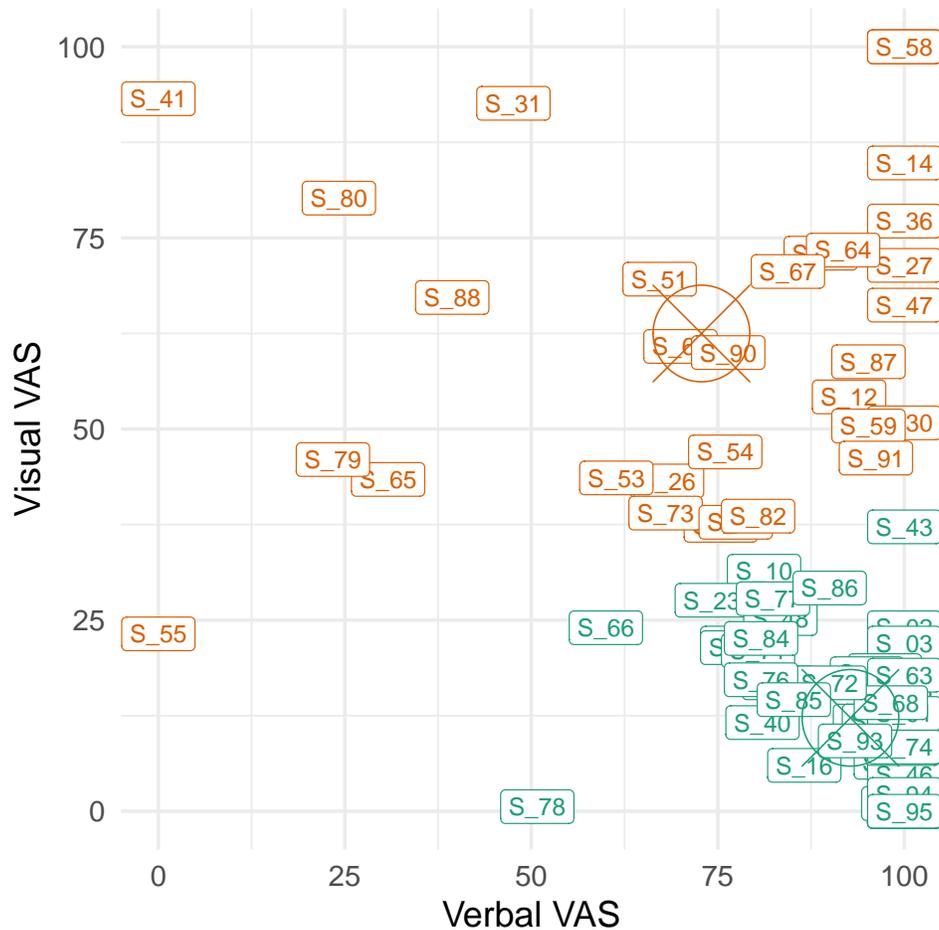


Figure 4. Results of the cluster analysis. The centroid of each cluster is represented by a circle and a central cross. The green cluster represents 'verbal ruminators' while the orange one represents 'visual ruminators'.

479 As can be seen from Figure 4 and from Table 4, this analysis revealed two groups of
 480 participants that were either *relatively* i) high on the verbal VAS and low on the visual one
 481 or ii) high on the visual VAS and low on the verbal one. However, participants included in
 482 the visual cluster remained quite high on the verblity scale. This result does not replicate
 483 the finding by Amit et al. (2017) that visual imagery is more spontaneous than verbal
 484 content, whatever the thinking mode.

Table 4

*Center and size (number of participants)
of the two clusters identified by the
k-means algorithm.*

Cluster	Verbal VAS	Visual VAS	Size
1	92.78	12	53
2	72.81	62	32

485 We then fitted the same model as we previously did but using the cluster (instead of
486 the “group”) as a predictor to assess the influence of the nature of ruminative thoughts on
487 the standardised EMG amplitude of each muscle. Estimations from this model are
488 reported in Table 5 and revealed no evidence for a difference between clusters on any
489 muscle (i.e., the BF_{01} for the effect of *cluster* was superior to 1 for every muscle).

Table 5

Estimates from the multivariate (weighted) Skew-Normal model based on the k-means clusters.

Response	Term	Estimate	SE	Lower	Upper	Rhat	BF01
OOI	Intercept	1.235	0.191	0.873	1.624	1.000	1.562×10^{-16}
OOI	cluster	0.004	0.289	-0.552	0.592	1.000	3.585
ZYG	Intercept	-0.047	0.042	-0.124	0.040	1.000	11.916
ZYG	cluster	0.019	0.072	-0.121	0.163	1.000	13.417
FRO	Intercept	1.592	0.219	1.183	2.046	1.000	2.999×10^{-16}
FRO	cluster	-0.618	0.373	-1.368	0.106	1.000	0.683
NEK	Intercept	-0.002	0.032	-0.063	0.064	1.000	32.198
NEK	cluster	-0.086	0.058	-0.200	0.031	1.000	5.858
FCR	Intercept	-0.020	0.046	-0.108	0.075	1.000	20.076
FCR	cluster	0.016	0.084	-0.149	0.183	1.000	12.364

Note. For each muscle (response), the first line represents the estimated average amplitude after the rumination induction and its standard error (SE). The second line represents the estimated average difference between the two types of induction (verbal vs. visual). The 'Lower' and 'Upper' columns contain the lower and upper bounds of the 95% CrI, whereas the 'Rhat' column reports the Gelman-Rubin statistic. The last column reports the BF in favour of the null hypothesis.

490 ***Relation between self-reports and EMG amplitude.***

491 We represent the relation between self-reported levels of state rumination (after
 492 induction) and the EMG amplitude (of the four facial muscles) changes from baseline to
 493 post-induction in Figure 5. This figure reveals an overall positive association between the

494 level of self-reported state rumination after induction and the increase in EMG amplitude
 495 from baseline to post-induction on the FRO muscle, but no substantial relation concerning
 496 the other muscles.

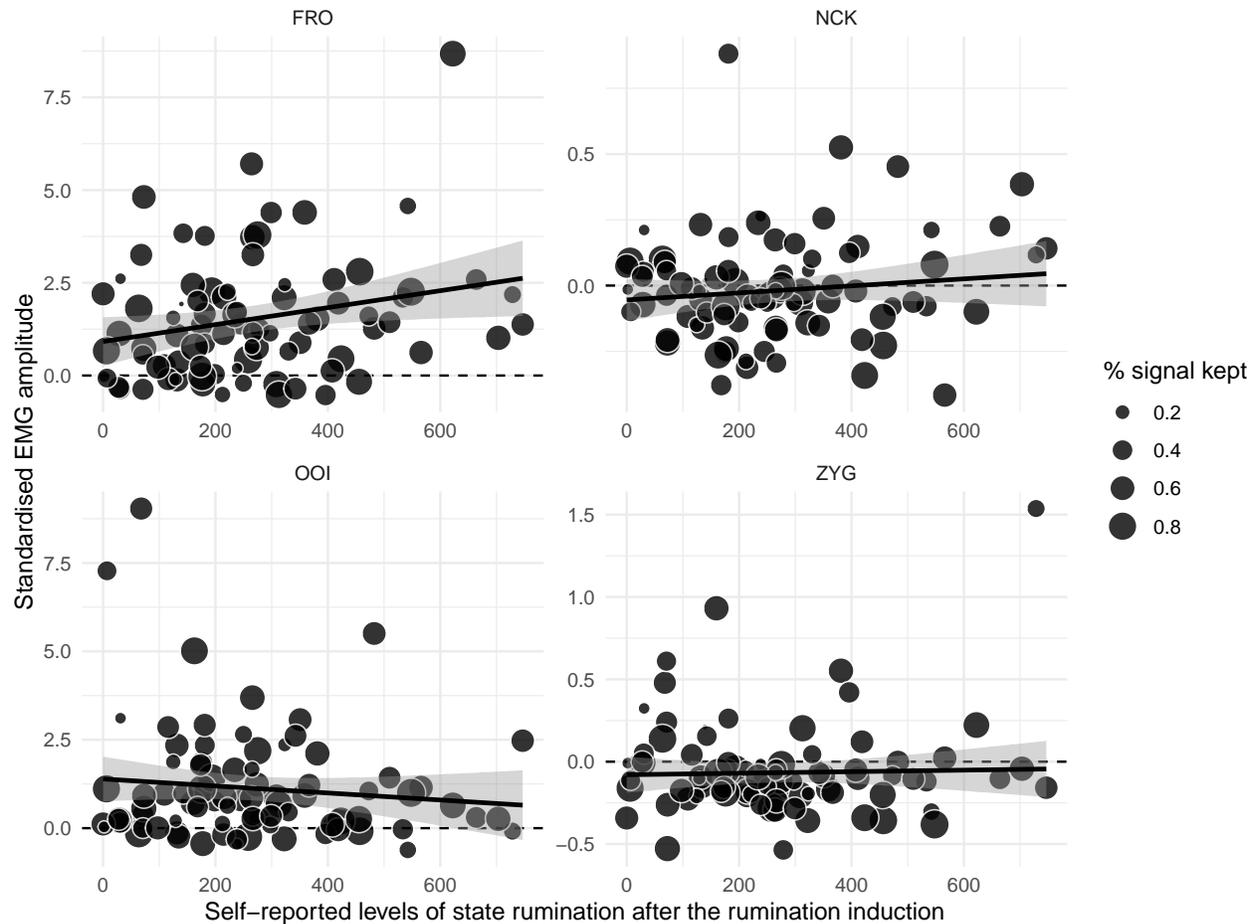


Figure 5. Relation between self-reported levels of state rumination (on the x-axis) and standardised EMG amplitude after the rumination induction (on the y-axis). The dots represent individual observations, whose size varies with the percentage of signal that was kept after removing artefacts. The black line represents the MLE regression line along with its 95% CI.

497 To further analyse the relationship between self-reported levels of state rumination
 498 and standardised EMG amplitude, we fitted a weighted multivariate Skew-Normal model
 499 (as previously). Estimations from this model are reported in Table 6.

Table 6

Estimates from the multivariate (weighted) Skew-Normal model assessing the relation between self-reported levels of state rumination and standardised EMG amplitude.

Response	Term	Estimate	SE	Lower	Upper	Rhat	BF01
OOI	Intercept	1.231	0.188	0.884	1.621	1.000	1.138*10 ⁻¹⁶
OOI	bsri	-0.052	0.147	-0.354	0.223	1.000	6.837
ZYG	Intercept	-0.044	0.041	-0.123	0.042	1.000	12.478
ZYG	bsri	0.000	0.036	-0.072	0.070	1.000	27.993
FRO	Intercept	1.497	0.217	1.093	1.949	1.000	6.206*10 ⁻¹⁷
FRO	bsri	0.229	0.194	-0.152	0.606	1.000	2.579
NEK	Intercept	-0.013	0.033	-0.074	0.054	1.000	27.698
NEK	bsri	0.005	0.034	-0.061	0.071	1.000	28.908
FCR	Intercept	-0.021	0.045	-0.108	0.072	1.000	19.679
FCR	bsri	0.027	0.042	-0.056	0.107	1.000	19.618

Note. For each muscle (response), the first line represents the estimated average amplitude after the rumination induction and its standard error (SE). The second line represents the estimated relation between self-reported levels of state rumination and standardised EMG amplitude. As the BSRI scores have been centered and standardised, this estimate approximate a correlation coefficient. The 'Lower' and 'Upper' columns contain the lower and upper bounds of the 95% CrI, whereas the 'Rhat' column reports the Gelman-Rubin statistic. The last column reports the BF in favour of the null hypothesis.

500 This analysis revealed a weak positive association between self-reported levels of state
 501 rumination (BSRI score) after induction and the standardised EMG amplitude recorded
 502 over the FRO muscle ($\beta = 0.229$, 95% CrI [-0.152, 0.606], $\text{BF}_{01} = 2.579$). This analysis

503 revealed no evidence for an association between self-reported levels of state rumination and
504 the standardised EMG amplitude recorded over the other muscles.

505 In summary, while successful in inducing higher levels of state rumination (higher
506 BSRI scores), the rumination induction did not permit to induce rumination in different
507 modalities. When examining groups of verbal vs. visual ruminators on the basis of VAS
508 levels, we did not find any evidence for specific electromyographic correlates. Interestingly,
509 we observed a weak positive correlation between self-reported levels of state rumination
510 and the standardised EMG amplitude of the FRO (see supplementary materials for
511 additional analyses).

512 **Effects of the relaxation**

513 **Planned (preregistered) analyses.** We hypothesised that orofacial relaxation
514 would cause a stronger decrease of state rumination than a relaxation targeting the arm,
515 for the participants that went through a verbal rumination induction, in comparison to a
516 non-verbal rumination induction. In other words, we expected an interaction effect between
517 the type of rumination induction and the type of relaxation. As the relaxation was directly
518 targeted at the facial muscles, we did not expect the overall EMG amplitude to be a
519 reliable index of ongoing rumination in this part of the experiment. Therefore, we only
520 report an analysis of the self-reported levels of state rumination (but see the supplementary
521 materials for additional analyses).

522 To analyse this interaction effect, we fitted a Gaussian model with a constant effect of
523 *group* (verbal vs. non-verbal rumination induction) and *relaxation* (orofacial vs. arm
524 relaxation) to predict the difference in BSRI score (after minus before the relaxation).
525 Estimations from this model are reported in Table 7.

Table 7

Estimated changes in self-reported levels of state rumination (BSRI scores).

Term	Estimate	SE	Lower	Upper	Rhat	BF01
Intercept	-91.69	13.75	-118.58	-64.41	1.00	-1.081*10 ⁻¹⁷
group	-0.04	26.80	-52.87	52.42	1.00	3.783
relax_type	23.82	26.83	-29.27	75.91	1.00	2.546
group:relax_type	26.02	49.07	-70.30	121.85	1.00	1.794

Note. For each effect, the 'Estimate' reports the estimated change in BSRI scores, followed by its standard error (SE). The 'Lower' and 'Upper' columns contain the lower and upper bounds of the 95% CrI, whereas the 'Rhat' column reports the Gelman-Rubin statistic. The last column reports the BF in favour of the null hypothesis.

526 This analysis revealed a general decrease in self-reported levels of state rumination
 527 after relaxation ($\beta = -91.688$, 95% CrI [-118.581, -64.408], $BF_{01} < 0.001$) but no
 528 substantial interaction effect with the relaxation type or the induction type (all BF_{01} were
 529 superior to 1). As two-way and three-way interaction terms are difficult to interpret
 530 numerically, we represent the raw data along with the model predictions in Figure 6. This
 531 Figure supports the conclusion that we did not observe any interaction effects (the line
 532 were parallel and with similar slopes across panels).

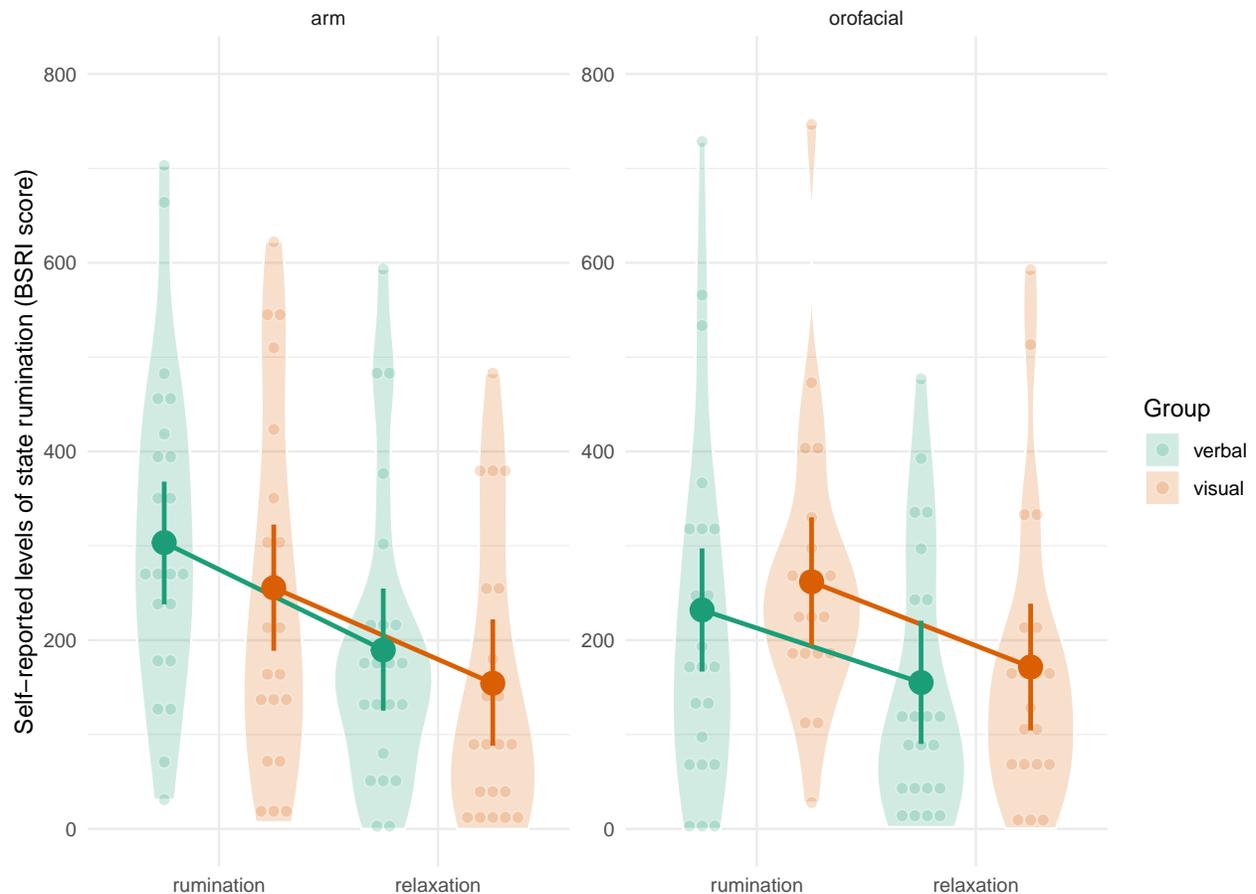


Figure 6. Self-reported levels of state rumination (BSRI score) by condition. The left panel depicts results in the orofacial relaxation group while the right panel depicts results in the arm relaxation group. Verbally-induced participants are represented in green whereas visually-induced participants are represented in orange. Individual observations (each participant) are represented by the smaller coloured dots whereas estimated means and 95% CrI are represented by the bigger surimposed coloured circles and vertical error bars.

533 The three way interaction term (the last line of Table 7) indicates that the
 534 interaction between condition (time) and the type of relaxation was slightly different
 535 according to the type of induction type ($\beta = 26.018$, 95% CrI [-70.301, 121.851], $BF_{01} =$
 536 1.794). However, the large uncertainty associated with this three-way interaction effect (as
 537 expressed by the SE and the width of the credible interval) prevents any strong conclusion.

538 Moreover, the sign of the BF supports the null hypothesis (although weakly in magnitude).

539 To sum up, we did not find evidence for an interaction effect between the type of
540 induction (verbal vs. non verbal) and the type of relaxation (orofacial versus arm) on
541 self-reported levels of state rumination. We turn now to a general summary and discussion
542 of the overall results.

543 Discussion

544 With this study we aimed to replicate and extend previous findings showing that
545 induced rumination was associated with increased facial muscular activity as compared to
546 rest (Nalborczyk et al., 2017). More precisely, we tried to disentangle the facial
547 electromyographic correlates of induced rumination that were related to either rumination
548 as a kind of inner speech or rumination as a state of pondering on negative affect. To this
549 end, we compared two types of rumination induction. The first one was designed to
550 specifically induce rumination in a verbal modality, whereas the second one was designed to
551 induce rumination in a visual modality. Following the *motor simulation view* of inner
552 speech production, we hypothesised that the verbal rumination induction should result in
553 higher activity in the speech-related muscles than the non-verbal rumination induction. At
554 the same time, forehead muscular activity should vary consistently (i.e., should not differ)
555 across conditions, as both conditions were expected to induce similar levels of negative
556 affect. Following the *motor simulation view* as well as previous observations (Nalborczyk et
557 al., 2017), we also hypothesised that relaxation focused on the orofacial area should be
558 more efficient in reducing rumination (when experienced in a verbal modality) than
559 relaxation focused on a non-orofacial area (i.e., the arm).

560 To examine these hypotheses, it was crucial to first show that i) the rumination
561 induction was successful in inducing rumination and ii) that the two types of rumination

562 induction were effectively inducing different types of rumination (i.e., verbal vs. non-verbal
563 rumination). Although our results show that the rumination induction was successful in
564 inducing rumination (as expressed by the increase in self-reported state rumination), it
565 failed to induce rumination in different modalities. That is, there was no difference in
566 self-reported levels of verbal versus visual thoughts, and no substantial difference in the
567 facial EMG correlates across conditions. Moreover, even when defining groups of verbal
568 versus visual ruminators a posteriori (i.e., based on the self-reports), these two groups were
569 not discriminable by their facial EMG recordings. However, it should be noted that both a
570 posteriori groups of participants were high on the verblivity scale. This last finding does not
571 replicate the observation by Amit et al. (2017) that verbal content occurs less
572 spontaneously than visual content in wilful thinking. Further studies are therefore needed
573 to examine modality during unwillful thinking, and especially rumination. In addition,
574 self-reported levels of state rumination were only (positively) related to the EMG
575 amplitude of the forehead muscle (FRO), but were not related to the activity of the other
576 facial muscles. In the second part of the experiment, comparing the two types of relaxation
577 (focused on the orofacial area or on the arm) revealed no difference in terms of their impact
578 on state rumination, whatever the type of rumination induction participants went through.
579 We discuss each of these results in the following sections.

580 **Inducing rumination in different modalities**

581 Based on the self-reports of verbal and visual thoughts assessed at the end of the
582 rumination period (cf. Table 3), both induction types led to similar ratios of verbal to
583 visual self-reported rumination. However, the fact that we did not find modality-specific
584 electromyographic correlates of rumination when contrasting groups of participants a
585 posteriori still poses a challenge to the *motor simulation view* (even though the two a
586 posteriori groups both reported verbal rumination, the “visual rumination group” would be

587 expected to simulate speech production less than the other group). As mentioned in the
588 Introduction, rumination can be conceptualised as a mental habit (Watkins &
589 Nolen-Hoeksema, 2014).

590 Habitual behaviours are more automatic than non-habitual behaviours, they are less
591 conscious and are often less controllable. In other words, frequent ruminators do not
592 willingly engage in ruminative thinking. Instead, rumination might be triggered by
593 contextual cues such as a negative mood, without the explicit evocation of a goal (or
594 discrepancy toward this goal). According to a recent neurocognitive model of inner speech
595 production (Løevenbruck et al., 2018), inner speech is considered as an action on its own
596 (as overt speech is), except that multimodal sensory consequences of speech are simulated.
597 This model also suggests that different forms of inner speech might involve the speech
598 motor system to a different extent (Grandchamp et al., 2019; Løevenbruck, 2019). More
599 precisely, highly expanded forms of inner speech (e.g., subvocally rehearsing a phone
600 number) are hypothesised to recruit the speech apparatus to a greater extent than more
601 evasive and more condensed forms of inner speech. Accordingly, we speculate that
602 rumination might be considered as a spontaneous (in opposition to deliberate) form of
603 inner speech that does not require a full specification of articulatory features.

604 If this hypothesis is correct, namely if rumination usually takes a more condensed
605 form, we should not expect to observe peripheral muscular activity during rumination.
606 Consequently, we need to explain the increased EMG amplitude recorded over the OOI
607 after the rumination induction that was observed in this experiment (but also in
608 Nalborczyk et al., 2017). Given that the level of activity in OOI increased more than in
609 ZYG after rumination induction, two interpretations are possible. First, it could be that
610 OOI reflects some implication of the speech motor system related to rumination. Even
611 though rumination is presumably expressed in a condensed form, it might contain some
612 fully expanded instances. The fact that the activity in the ZYG did not increase could be

613 explained by its weak involvement in non hyper-articulated speech production (a finding
614 also obtained by Rapin et al., personal communication). The fact that the increase in OOI
615 activity is not proportional to the degree of self-reported state rumination could be due to
616 the fact that condensed instances of rumination overweigh the more expanded instances. A
617 second interpretation could be that the OOI activity reflects in fact negative mood
618 (cf. Ekman's action units 22, 23, 24) or cognitive effort (van Boxtel & Jessurun, 1993;
619 Waterink & van Boxtel, 1994). The stability in the level of activity of the ZYG muscle is
620 compatible with this second interpretation.

621 Finally, another explanation for the absence of modality-specific EMG correlates
622 might come from previous studies using surface EMG to investigate inner speech
623 production. As summarised in the previous section, our results do not support theoretical
624 predictions of the *motor simulation view*, according to which it should be possible to
625 discriminate the content of inner speech (and rumination) based on peripheral muscular
626 activation. Nevertheless, the outcome of the present study is consistent with the results
627 reported by Meltzner et al. (2008). These authors were able to obtain high classification
628 accuracies during both overt and mouthed speech but not during covert speech (despite the
629 fact that they used eleven sensors on the neck and the lower face).

630 However, the results of Meltzner et al. (2008) (and ours) stand in sharp contrast with
631 classical results on the electromyographic correlates of inner speech production (e.g.,
632 McGuigan & Dollins, 1989; McGuigan & Winstead, 1974; Sokolov, 1972) as well as more
633 recent developments. For instance, Kapur et al. (2018) developed a wearable device
634 composed of seven surface EMG sensors that can attain a 92% median classification
635 accuracy in discriminating internally vocalised digits. These discrepant results could be
636 explained by differences in the methodology employed by these different teams (see
637 discussion in Nalborczyk, Grandchamp, et al., 2020). Indeed, the between-subject nature of
638 the designs investigating the effects of induced rumination might hamper the possibility of

639 highlighting modality-specific EMG correlates. Because (surface) electromyography is only
640 a noisy indicator of inner speech production, decoding the content of inner speech based on
641 such signals require multiple measurements per individual, and possibly participant-specific
642 recording characteristics. Therefore, the lack of modality-specific EMG correlates might
643 also be explained by a lack of sensitivity of the design we describe in the current article.

644 We think this possibility might be examined by looking at the results obtained in the
645 second part of the experiment. If the absence of modality-specific EMG correlates is only
646 due to a lack of sensitivity, state rumination should still be more disrupted by an orofacial
647 relaxation than by a non-orofacial relaxation.

648 A few additional words of caution are necessary. Our results were obtained using a
649 controlled rumination induction situation, which, for ethical reasons, did not have serious
650 consequences for the future lives of our participant. This is far from real-life ruminative
651 situations in which participants are more engaged. Therefore, the observed effects on the
652 experimental variables may have been weakened, because of a lack of engagement in the
653 situation. For the same reason, the verbal versus visual induction difference might have
654 been diminished due to a lack of compliance. Finally, the weakness of the effects obtained
655 could also be due to the specific population. Participants were only included if they scored
656 low on the CES-D. Stronger effects could be expected with participants more predisposed
657 to depression.

658 **Modality-specific and effector-specific relaxation effects**

659 Contrary to our predictions, we did not observe the interaction effect between the
660 type of rumination induction (verbal vs. non-verbal) and the type of relaxation (orofacial
661 relaxation vs. arm relaxation). This null result also persisted when considering the
662 interaction between the a posteriori cluster and the type of relaxation (see supplementary

663 materials). Moreover, BF-based hypothesis testing revealed no evidence for a difference
664 between the two types of relaxation⁴ (cf. Table 7 and Figure 6). However, looking in more
665 details into the estimations from this model reveals that the arm relaxation was estimated
666 to be more efficient than the orofacial relaxation in reducing self-reported levels of state
667 rumination (BSRI scores). More precisely, the difference between the two types of
668 relaxations was estimated to be of around 25 points on the scale of the BSRI sum score,
669 although the large uncertainty associated with this estimation prevents any strong
670 conclusion.

671 Interestingly, these results are contradicting those of Nalborczyk et al. (2017), who
672 observed a stronger decrease in self-reported state rumination following the orofacial
673 relaxation than the arm relaxation. However, it should be noted that both the results of
674 Nalborczyk et al. (2017) and the results reported in the current article are based on
675 comparisons involving relatively low sample sizes (two groups of around 20 participants
676 and two groups of around 40 participants, respectively). As such, these results should be
677 considered at most as suggestive.

678 Nevertheless, the high similarity between these two studies warrants a
679 meta-analytical way of thinking about their results. In other words, given that both studies
680 used a similar rumination induction and the same relaxation recordings, we can compute
681 an average effect size across these two studies to get a more accurate estimate of the
682 population effect size. The effect size (pooled Cohen's d) for the difference between the two
683 types of relaxation was of $\delta = -0.498$ (95% CI [-1.095, 0.098]) in Nalborczyk et al. (2017)
684 and of $\delta = 0.207$ (95% CI [-0.225, 0.64]) in the current article. Because the current study

⁴ Neither did it reveal evidence for a difference, as the BF was close to 1. A Bayes factor around 1 means that the observed data is similarly likely to appear under both the hypothesis of an effect being different from zero and the hypothesis of a null effect. Moreover, it should be noted that BFs are extremely dependent on prior assumptions. As such, the obtained BFs might vary substantially by varying the prior assumptions of the fitted models.

685 has a larger sample size, the uncertainty (the width of the CI) about the value of the
686 Cohen's d is smaller. Therefore, weighting both estimates by their respective standard
687 error reveals an average effect size that is very close to zero ($\delta = -0.05$).

688 To sum up, we did not observe a stronger effect of the orofacial relaxation (when
689 compared to the non-orofacial relaxation) and we did not observe the hypothesised
690 interaction effect between the type of rumination induction and the type of relaxation.
691 Moreover, we also did not observe an interaction between the type of rumination induction
692 and the clusters defined a posteriori (see supplementary materials). These results taken
693 together corroborate the hypothesis formulated previously, according to which rumination
694 –as a mental habit (Watkins & Nolen-Hoeksema, 2014)– could be considered as a strongly
695 internalised and condensed form of inner speech. As such, ruminative thinking would not
696 *require* the involvement of the speech motor system. Therefore, rumination is not expected
697 to be disrupted by motor interferences such as relaxation or articulatory suppression
698 (Nalborczyk, Perrone-Bertolotti, et al., 2020).

699 **Conclusions**

700 We examined whether rumination is better described as a form of inner speech that
701 requires the motor simulation of speech production, or as a rather abstract and articulatory
702 impoverished form of inner speech. In the first case, verbal rumination should be
703 accompanied by an activation of the speech muscles and should be disrupted by motor
704 interference directed at the speech muscles. To examine these hypotheses, we extended a
705 previous study (Nalborczyk et al., 2017) and compared two types of rumination induction
706 designed to elicit either verbal or non-verbal (visual) rumination.

707 In the first part of the experiment, we replicated the findings of Nalborczyk et al.
708 (2017) by showing that both the activity of the forehead (FRO) and the activity of the lip

709 (OOI) was higher than baseline after a rumination induction (averaging across the two
710 types of rumination induction). However, we failed to find distinct EMG correlates when
711 comparing the two types of rumination induction or when comparing two (a posteriori
712 defined) groups of verbal vs. visual ruminators (although both groups showed a relatively
713 high levels of verbal thoughts). Moreover, only the activity of the forehead was related to
714 self-reported state rumination. In the second part of the experiment, we did not observe
715 the hypothesised interaction effect between the type of induction and the type of
716 relaxation. More precisely, following the *motor simulation view* of inner speech production,
717 we expected to observe a stronger decrease in self-reported state rumination following an
718 orofacial relaxation than a non-orofacial relaxation, when rumination was expressed in a
719 verbal modality (as compared to a non-verbal modality). This prediction was not
720 supported by the data. Taken together, these results suggest that verbal rumination is an
721 impoverished form of inner speech that is not fully specified at an articulatory level.

722 We speculated that this observation might be explained by the degree of automaticity
723 that usually accompanies rumination. Following the mental habit view of rumination
724 (Watkins & Nolen-Hoeksema, 2014), rumination can be considered as a habitual mode of
725 response to contextual cues (e.g., negative mood). As such, it can be considered as a
726 non-intentional (or weakly intentional) form of inner speech. Thus, the absence of
727 modality-specific correlates of verbal rumination is congruent with the observation that
728 inner speech is more strongly accompanied by peripheral muscular activation when
729 expressed intentionally or under adverse conditions (e.g., Sokolov, 1972).

730 Some limitations are worth keeping in mind when interpreting these results. First,
731 the current sample only consisted of female participants. Whereas it permitted to maximise
732 the probability of effectively inducing rumination, it also limits the generalisability of these
733 findings. Second, although the rumination induction resulted in slightly different levels of
734 self-reported levels of verbal thoughts, this difference was weak. Instead of *inducing*

735 rumination in different modalities, a more fruitful strategy to compare the consequences of
736 verbal vs. non-verbal rumination might be to induce rumination in the “preferred”
737 modality of the participant. We might recruit participants with a propensity to ruminate
738 preferentially in one of those modalities and present them with a classical rumination
739 induction procedure. This would arguably increase the contrast between the two type of
740 inductions and the probability of observing modality-specific EMG correlates, if any.

741 Nevertheless, these results provide relevant information for both the study of
742 repetitive negative thinking (including rumination) and the study of inner speech. On the
743 first hand, the strong internalisation and condensation of verbal rumination speaks in
744 favour of the conception of rumination as a mental habit (Watkins & Nolen-Hoeksema,
745 2014). On the other hand, the modulation of the involvement of the speech motor system
746 during inner speech by its degree of automaticity is congruent with previous observations.
747 However, these results still need to be replicated and further developed before being
748 incorporated into integrative neurocognitive models of inner speech production.

749 **Supplementary materials**

750 Pre-registered protocol, open data, supplementary analyses as well as reproducible
751 code and figures are available at <https://osf.io/c9pag/>.

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755 2018; Lüdecke, 2018), the `biosignalEMG` and `R.matlab` packages for signal processing
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758

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