Dissociating facial electromyographic correlates of visual and verbal induced rumination

Ladislas Nalborczyk, Sonja Banjac, Céline Baeyens, Romain Grandchamp, Ernst H.W. Koster, Marcela Perrone-Bertolotti, Hélène Lœvenbruck

Dissociating facial electromyographic correlates of visual and verbal induced rumination

Ladislas Nalborczyk[1,2,3*], Sonja Banjac[1*], Céline Baeyens[4], Romain Grandchamp[1], Ernst H. W. Koster[2], Marcela Perrone-Bertolotti[1,5], & Hélène Lœvenbruck[1]

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

[2] Department of Experimental Clinical and Health Psychology, Ghent University

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

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

[5] Institut Universitaire de France (IUF), France

Author Note

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

Abstract

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

Keywords: rumination, repetitive negative thinking, inner speech, covert speech, electromyography, simulation, emulation

Dissociating facial electromyographic correlates of visual and verbal induced rumination

Word-count (excluding abstract, references, tables and figures): 9048

Introduction

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

Defining rumination

Rumination can be broadly defined as unconstructive repetitive thinking about past events and current mood states (Martin & Tesser, 1996). One of the most influential frameworks of rumination is the *Response Style Theory* (RST, Nolen-Hoeksema, 1991; Nolen-Hoeksema et al., 2008) that describe rumination as a behavioural pattern that is characterised by perseverative, repetitive, and passive thought. According to the RST, individuals who are experiencing rumination are repetitively focusing on their negative emotional state, on the fact that they are feeling depressed, and on the causes and consequences of their symptoms (Nolen-Hoeksema, 1991). In this framework, rumination is viewed as a type of response to distress or a coping mechanism which involves focusing the attention on oneself and one's current emotional state (Nolen-Hoeksema, 1991). Alloy, Robinson and colleagues (Alloy et al., 2000; Robinson & Alloy, 2003; Smith & Alloy, 2009) also suggested that rumination can also appear following stressful life events, before the start of the depressive mood.

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

The nature of ruminative thoughts

Rumination has sometimes been portrayed as a form of *inner speech* (Perrone-Bertolotti et al., 2014) due to its predominantly verbal character (Ehring & Watkins, 2008; Goldwin et al., 2013; Goldwin & Behar, 2012; McLaughlin et al., 2007). However, what inner speech precisely entails is still debated (for a recent review, see Lœvenbruck et al., 2018). In the present paper, we examine the *motor simulation view* that considers inner speech production to be the result of a mental simulation of overt speech (Jeannerod, 2006; Postma & Noordanus, 1996). Inner speech is hence conceived as (inhibited) speech motor acts that trigger –via a *simulation* or an *emulation* mechanism– multimodal sensory percepts (Lœvenbruck et al., 2018). This perspective entails that the speech motor system should be involved during inner speech production and that we could record a peripheral residual activity in the speech muscles. This hypothesis has been corroborated by several studies using orofacial surface electromyography (EMG) during tasks that involve inner speech production such as silent recitation, verbal mental imagery or problem solving (Jacobson, 1931; Livesay et al., 1996; McGuigan & Dollins, 1989; Sokolov, 1972).

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

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

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

Manipulation of rumination modality

Although several studies explored how much ongoing rumination was verbal or visual (e.g., Goldwin & Behar, 2012; McLaughlin et al., 2007), only a few studies experimentally manipulated the *modality* of rumination. Some of the few studies specifically manipulating verbal and visual rumination were carried out by Zoccola and colleagues (Woody et al., 2015; Zoccola et al., 2014). The verbal or visual form of rumination was induced by playing audio tapes that directed participants' thoughts. Prompts were similar in both conditions, differing only in the verbal/visual instruction ("Recall the speech task using words, phrases, and sentences." vs. "Recall the speech task using pictures and images."). Participants were subsequently asked to estimate the proportion of verbal thoughts and mental visual images. Although not directly focused on rumination, the task developed by Holmes et al. (2008) is inspiring for exploring rumination in different modalities. These authors aimed to compare verbal and imagery processing in terms of their differential effects on emotion. They noticed that previous procedures provided verbal descriptions of the events that needed to be processed verbally or visually. The authors argued that with such descriptions, the imagery condition has an additional processing mode in comparison to the verbal condition. To make the verbal and imagery conditions more comparable in terms of processing load, they combined pictorial and verbal cues and asked participants to integrate them using either a sentence or an image.

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

The present study

There is a need for studies that induce verbal or visual rumination in order to inspect whether and how the experience of rumination in these two modalities differ (Lawrence et al., 2018). Furthermore, there has only been one set of studies, to the best of our knowledge, that has employed a protocol for specifically inducing verbal or visual rumination (Woody et al., 2015; Zoccola et al., 2014). In addition, there were a few shortcomings in this protocol, some of which were highlighted by the authors, such as the stress induction component. To tackle these issues, we extended the study presented in Nalborczyk et al. (2017) by inducing rumination in distinct modalities to compare their electromyographic correlates.

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

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

Methods

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

Participants

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

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

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

Material and EMG setup

The experimental procedure was developed using the OpenSesame software (Mathôt et al., 2012) and stimuli were displayed on a DELL computer screen of size 1280px*720px. TrignoTM Mini wireless sensors (Delsys Inc.) were used for the detection of the surface EMG signals. These sensors consist of a bigger and a smaller box. The smaller box contains two 5x1mm parallel electrode bars with 10mm between them that record bipolar muscle activation. For facial EMG, the small box with electrodes was attached to the face and the bigger box was usually placed on the side of the neck. Concerning the forearm EMG, both boxes were placed on the forearm. Both boxes were attached by double-sided adhesive tape. Before setting the sensors, the skin was cleaned by Nuprep scrubbing gel and by alcohol wipes. Signal acquisition and synchronisation was done using the PowerLab 16/35 (ADInstrument, PL3516) device with a sampling rate of 1000 Hz. In addition to EMG measurements, the audio signal was simultaneously recorded using a C1000S AKG microphone which was placed 20-30 cm away from the participant. The audio signal was amplified using a Berhringer Tube Ultragain MIC100 amplifier. It was synchronised with the EMG signals using trigger signals. The experiment was video-monitored using a Sony HDR-CX240E camera. These recordings were taken in order to track any vocal or behavioural artefacts during periods of interest (i.e., baseline, rumination and relaxation). Labchart 8 software (ADInstrument, MLU60/8) was used for EMG and audio data collecting and processing.

Our exploration focused on the muscles that have already been found to be activated during covert or overt speech (e.g., Fromkin, 1966; Kennedy & Abbs, 1979; Laurent et al., 2016; Lieshout Pascal H. H. M. van et al., 1993; Maier-Hein et al., 2005; Schultz & Wand, 2010). With surface EMG, it is difficult to precisely relate a given skin position to a specific muscle. However, as authors often refer to the facial positions as muscle positions, we will follow this tradition for clarity. Because of their involvement in speech production, bipolar surface EMG electrodes were positioned on the orbicularis oris inferior (OOI), the zygomaticus major (ZYG), and on the neck region, potentially reflecting the activity of platysma and tongue muscles (NCK). It should be mentioned that in addition to their contribution to lip movement and configuration during speech, OOI and ZYG have also been associated with negative and positive valence emotions, respectively. Given that their involvement in emotion is of opposite direction, using both sites may help to disentangle between emotion- and speech-related activation. In addition, electrodes were also placed on the frontalis (FRO) as a non-speech but negative-emotion-related muscle. The corrugator supercilii muscle, often cited as a negative-emotion-related muscle (Tan et al., 2012), was not used because it is associated with eyebrow movements, which have been shown to accompany speech production (Bolinger, 1986; Krahmer & Swerts, 2004). Finally, we positioned a sensor on the flexor carpi radialis (FCR) to control for general (whole body) muscle contraction (see the supplementary materials for a depiction of the position of the sensors).

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

Procedure

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

Trait questionaires. After filling the consent form, participants were asked to complete the CES-D (Radloff, 1977). Participants also filled out the short version of the Ruminative Response Scale (RRS, Treynor et al., 2003), adapted and validated in French (Douilliez, Guimpel, Baeyens, & Philippot, in preparation). These questionnaires were filled in paper format. Once it was determined that they could participate in the study (i.e., that they did not exceed the threshold for depressive symptoms on the CES-D), participants were equipped with the EMG sensors.

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

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

Imagery training (verbal and visual modes). Next, participants went through a "lemon training" based on the task proposed by Holmes et al. (2008). The objective of this training was to show the participants precisely what was meant by *thinking in words* or *thinking in pictures*. The participants in the *verbal* group were asked to covertly generate an appropriate sentence combining an image (e.g., a lemon) and a caption word (e.g., "cut"), whereas participants in the *visual* group were asked to imagine a picture combining the image and the caption word. There were two trials. After each trial, participants rated how clear (how vivid) their sentence or image was, following which they had to say or describe it out loud. This served as a verification that participants did the task and that they understood it.

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

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

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

EMG signal processing

Data were collected using Labchart8 and were subsequently exported to Matlab for signal processing (www.mathworks.fr, Matlab r2015a, version 8.5.0.197613). First, a 50Hz frequency comb filter was applied to eliminate power noise. Then, in keeping with the recommendation for facial EMG studies (De Luca et al., 2010), a 20 Hz – 450 Hz bandpass filter was applied, in order to focus on the facial EMG frequency band. The EMG signal was centred to its mean and cut with respect to the three periods of interest (i.e., baseline, rumination and relaxation), all of which were divided into 5s blocks. These data were then exported to `R` version 3.5.0 (R Core Team, 2018), where the mean of the absolute signal was calculated for each 5s block. Thus, a score for each muscle, in each period, for each participant was calculated. Absolute EMG values are not meaningful as muscle activation is never null, even in resting conditions, due in part to physiological noise. In addition, there are inter-individual variations in the amount of EMG amplitude in the baseline. To normalise for baseline amplitude across participants, we thus subtracted the EMG amplitude of the baseline to the two periods of interest (i.e., after rumination and after relaxation) and divided it by the variability of the signal at baseline for each muscle and each participant.

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

Data analysis

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

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

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

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

Effects of the rumination induction and rumination modality

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

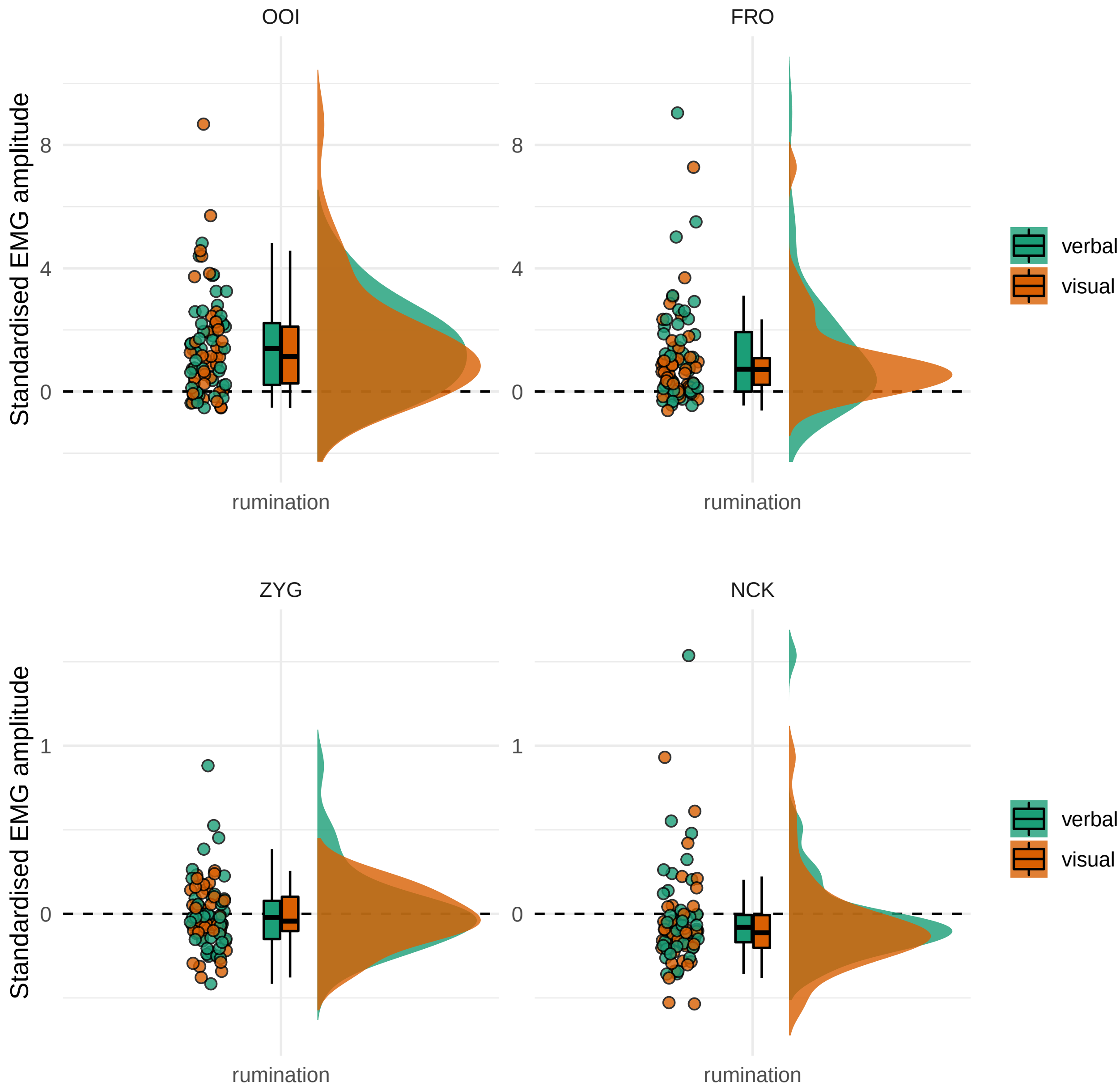

Figure 1. Standardised EMG amplitude during the rumination period. The coloured dots represent the mean standardised EMG amplitude by participant and by type of induction. The boxplot represents the median as well as the first and third quartiles. Note: the y-axis differs between the two rows.

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

rumination induction and the difference between the two types of rumination induction. 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.

This analysis revealed that the average EMG amplitude of both the OOI and the FRO muscles was estimated to be higher than baseline (the standardised score was above zero) after rumination induction. However, it was not the case for the ZYG, NCK, and FCR muscles. We did not observe the hypothesised difference according to the type of induction on the OOI (β = 0.204, 95% CrI [-0.467, 0.866], BF_{01} = 2.489) nor on the FRO (β = -0.066, 95% CrI [-0.728, 0.599], BF_{01} = 2.878).

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

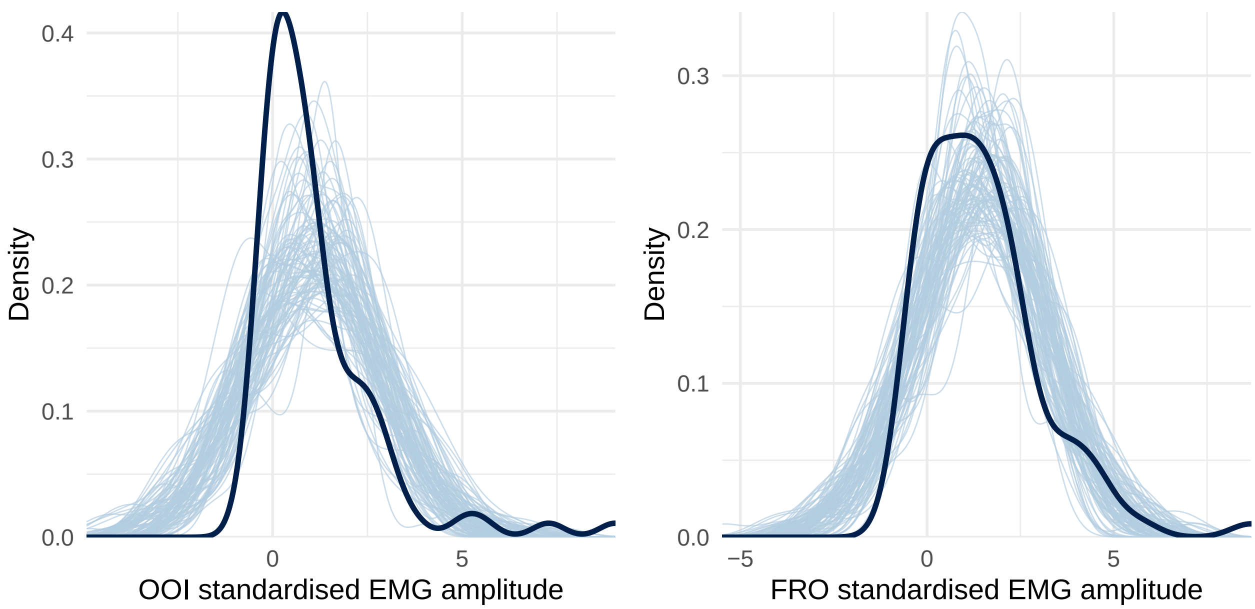

Figure 2. Posterior predictive checking for the first model concerning the OOI and FRO muscles. The dark blue line represents the distribution of the raw data while light blue lines are dataset generated from the posterior distribution.

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

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

This analysis revealed that the average EMG amplitude of both the OOI and the FRO muscles was estimated to be higher than baseline (the standardised score was above zero) after rumination induction. However, it was not the case for the ZYG, NCK and FCR muscles. We did not observe the hypothesised difference according to the type of induction on the OOI (β = -0.069, 95% CrI [-0.607, 0.491], BF_{01} = 3.553) nor on the FRO (β = -0.003, 95% CrI [-0.66, 0.673], BF_{01} = 3.156). The posterior predictive checks for this model are presented in Figure 3 and indicate that this model seems to better accommodate the collected data.

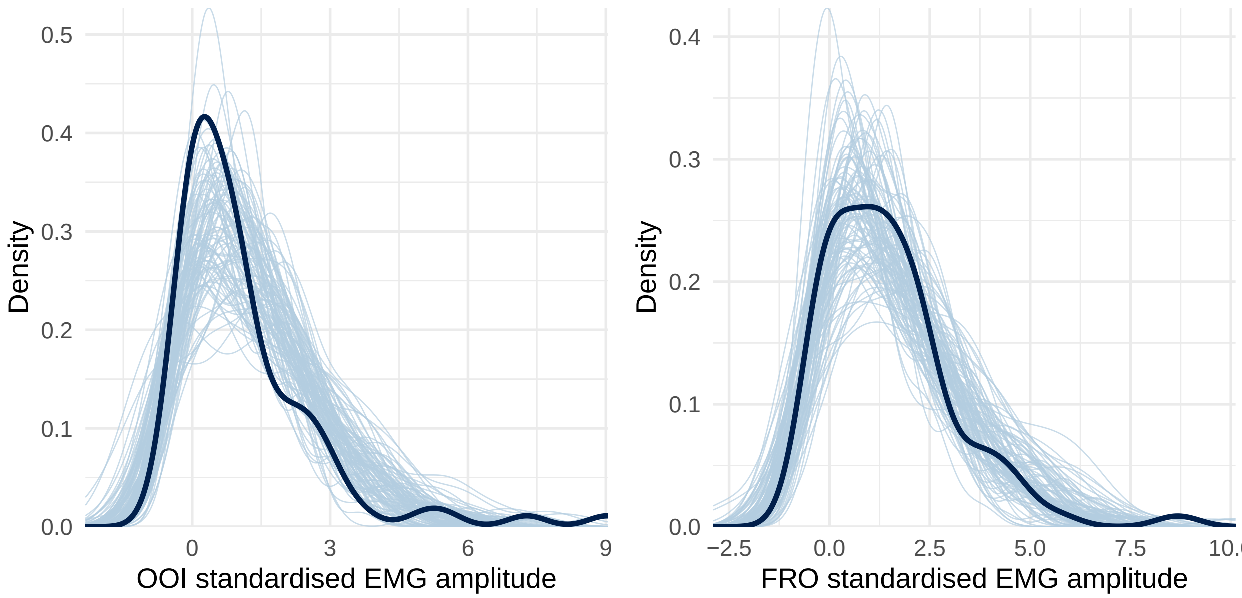

Figure 3. Posterior predictive checking for the Skew-Normal model concerning the OOI and FRO muscles. The dark blue line represents the distribution of the raw data while light blue lines are dataset generated from the posterior distribution.

Cluster analyses.

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

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

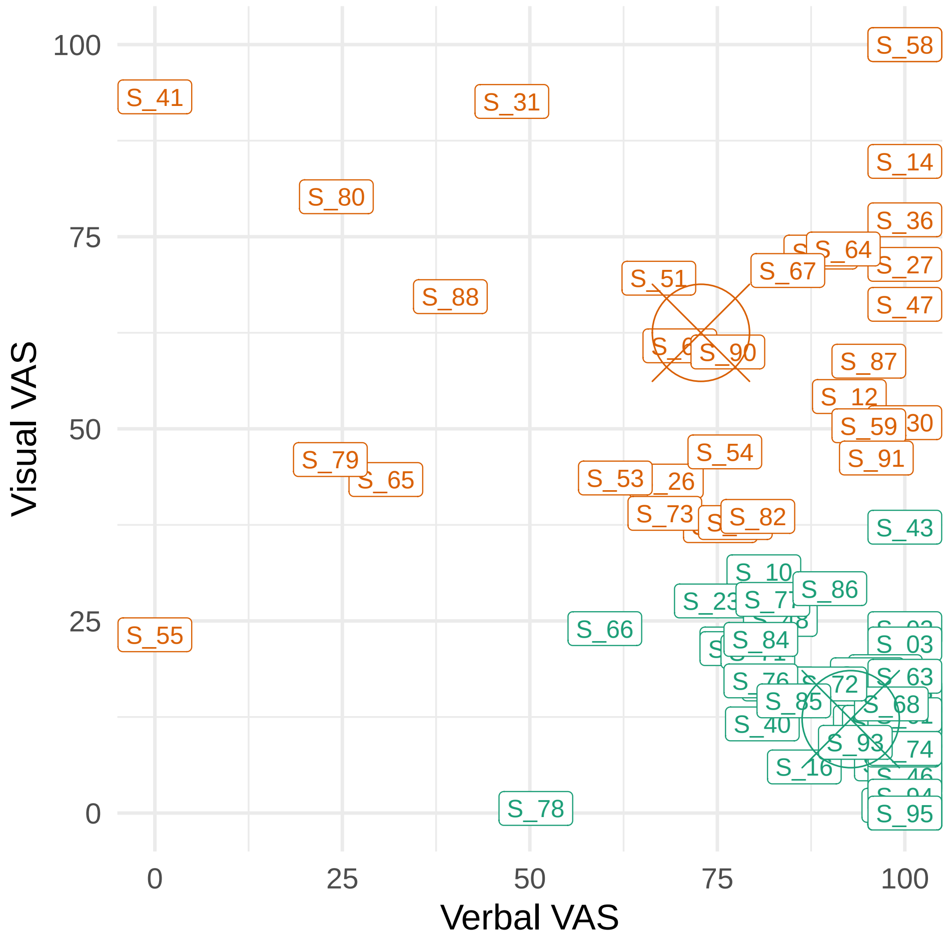

Figure 4. Results of the cluster analysis. The centroid of each cluster is represented by a circle and a central cross. The green cluster represents 'verbal ruminators' while the orange one represents 'visual ruminators'.

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

We then fitted the same model as we previously did but using the cluster (instead of the “group”) as a predictor to assess the influence of the nature of ruminative thoughts on the standardised EMG amplitude of each muscle. Estimations from this model are reported in Table 5 and revealed no evidence for a difference between clusters on any 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.

Relation between self-reports and EMG amplitude.

We represent the relation between self-reported levels of state rumination (after induction) and the EMG amplitude (of the four facial muscles) changes from baseline to post-induction in Figure 5. This figure reveals an overall positive association between the level of self-reported state rumination after induction and the increase in EMG amplitude from baseline to post-induction on the FRO muscle, but no substantial relation concerning the other muscles.

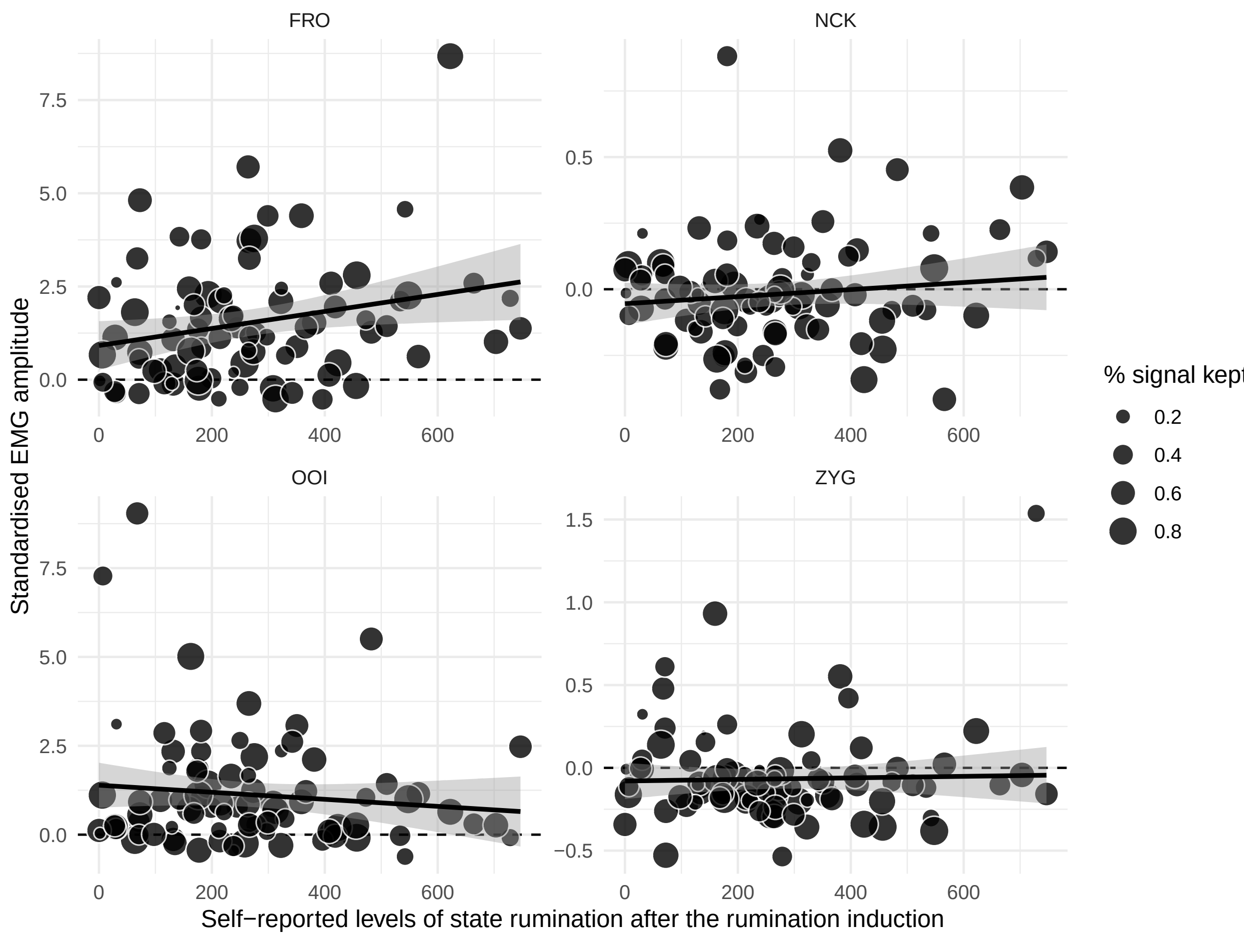

Figure 5. Relation between self-reported levels of state rumination (on the x-axis) and standardised EMG amplitude after the rumination induction (on the y-axis). The dots represent individual observations, whose size varies with the percentage of signal that was kept after removing artefacts. The black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

To further analyse the relationship between self-reported levels of state rumination and standardised EMG amplitude, we fitted a weighted multivariate Skew-Normal model (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.

This analysis revealed a weak positive association between self-reported levels of state rumination (BSRI score) after induction and the standardised EMG amplitude recorded over the FRO muscle ($\beta = 0.229$, 95% CrI [-0.152, 0.606], $BF_{01} = 2.579$). This analysis revealed no evidence for an association between self-reported levels of state rumination and the standardised EMG amplitude recorded over the other muscles.

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

Effects of the relaxation

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

To analyse this interaction effect, we fitted a Gaussian model with a constant effect of *group* (verbal vs. non-verbal rumination induction) and *relaxation* (orofacial vs. arm relaxation) to predict the difference in BSRI score (after minus before the relaxation). 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.

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

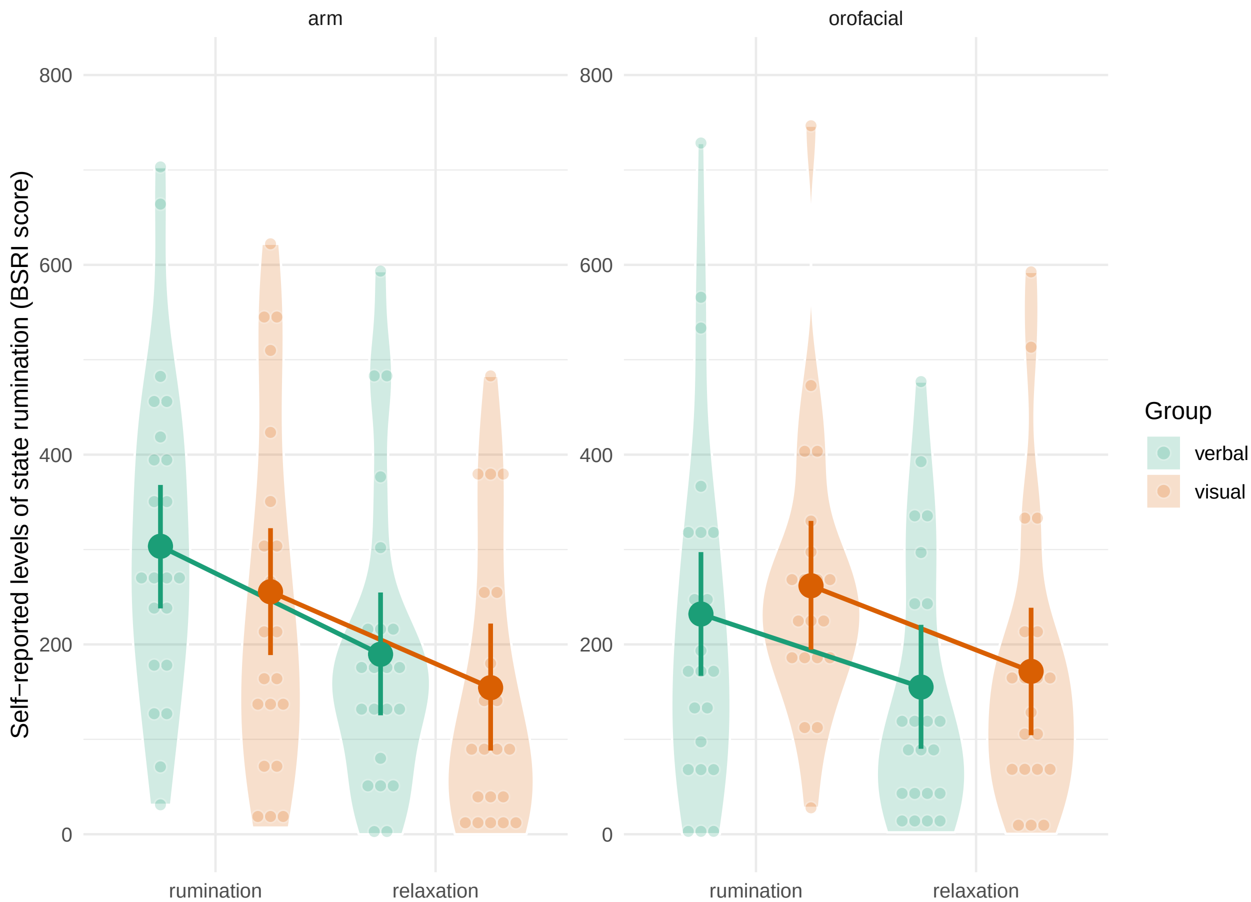

Figure 6. Self-reported levels of state rumination (BSRI score) by condition. The left panel depicts results in the orofacial relaxation group while the right panel depicts results in the arm relaxation group. Verbally-induced participants are represented in green whereas visually-induced participants 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.

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

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

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

Discussion

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

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

Inducing rumination in different modalities

Based on the self-reports of verbal and visual thoughts assessed at the end of the rumination period (cf. Table 3), both induction types led to similar ratios of verbal to visual self-reported rumination. However, the fact that we did not find modality-specific electromyographic correlates of rumination when contrasting groups of participants a posteriori still poses a challenge to the *motor simulation view* (even though the two a posteriori groups both reported verbal rumination, the "visual rumination group" would be expected to simulate speech production less than the other group). As mentioned in the Introduction, rumination can be conceptualised as a mental habit (Watkins & Nolen-Hoeksema, 2014).

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

If this hypothesis is correct, namely if rumination usually takes a more condensed form, we should not expect to observe peripheral muscular activity during rumination. Consequently, we need to explain the increased EMG amplitude recorded over the OOI after the rumination induction that was observed in this experiment (but also in Nalborczyk et al., 2017). Given that the level of activity in OOI increased more than in ZYG after rumination induction, two interpretations are possible. First, it could be that OOI reflects some implication of the speech motor system related to rumination. Even though rumination is presumably expressed in a condensed form, it might contain some fully expanded instances. The fact that the activity in the ZYG did not increase could be explained by its weak involvement in non hyper-articulated speech production (a finding also obtained by Rapin et al., personal communication). The fact that the increase in OOI activity is not proportional to the degree of self-reported state rumination could be due to the fact that condensed instances of rumination overweigh the more expanded instances. A second interpretation could be that the OOI activity reflects in fact negative mood (cf. Ekman's action units 22, 23, 24) or cognitive effort (van Boxtel & Jessurun, 1993; Waterink & van Boxtel, 1994). The stability in the level of activity of the ZYG muscle is compatible with this second interpretation.

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

However, the results of Meltzner et al. (2008) (and ours) stand in sharp contrast with classical results on the electromyographic correlates of inner speech production (e.g., McGuigan & Dollins, 1989; McGuigan & Winstead, 1974; Sokolov, 1972) as well as more recent developments. For instance, Kapur et al. (2018) developed a wearable device composed of seven surface EMG sensors that can attain a 92% median classification accuracy in discriminating internally vocalised digits. These discrepant results could be explained by differences in the methodology employed by these different teams (see discussion in Nalborczyk, Grandchamp, et al., 2020). Indeed, the between-subject nature of the designs investigating the effects of induced rumination might hamper the possibility of highlighting modality-specific EMG correlates. Because (surface) electromyography is only a noisy indicator of inner speech production, decoding the content of inner speech based on such signals require multiple measurements per individual, and possibly participant-specific recording characteristics. Therefore, the lack of modality-specific EMG correlates might also be explained by a lack of sensitivity of the design we describe in the current article.

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

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

Modality-specific and effector-specific relaxation effects

Contrary to our predictions, we did not observe the interaction effect between the type of rumination induction (verbal vs. non-verbal) and the type of relaxation (orofacial relaxation vs. arm relaxation). This null result also persisted when considering the interaction between the a posteriori cluster and the type of relaxation (see supplementary materials). Moreover, BF-based hypothesis testing revealed no evidence for a difference between the two types of relaxation[4] (cf. Table 7 and Figure 6). However, looking in more details into the estimations from this model reveals that the arm relaxation was estimated to be more efficient than the orofacial relaxation in reducing self-reported levels of state rumination (BSRI scores). More precisely, the difference between the two types of relaxations was estimated to be of around 25 points on the scale of the BSRI sum score, although the large uncertainty associated with this estimation prevents any strong conclusion.

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

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

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

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

Conclusions

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

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

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

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

Some limitations are worth keeping in mind when interpreting these results. First, the current sample only consisted of female participants. Whereas it permitted to maximise the probability of effectively inducing rumination, it also limits the generalisability of these findings. Second, although the rumination induction resulted in slightly different levels of self-reported levels of verbal thoughts, this difference was weak. Instead of *inducing* rumination in different modalities, a more fruitful strategy to compare the consequences of verbal vs. non-verbal rumination might be to induce rumination in the “preferred” modality of the participant. We might recruit participants with a propensity to ruminate preferentially in one of those modalities and present them with a classical rumination induction procedure. This would arguably increase the contrast between the two type of inductions and the probability of observing modality-specific EMG correlates, if any.

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

Supplementary materials

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

Many packages have been used for the writing of this paper, among which the `BEST`, `patchwork` and `ggplot2` packages for plotting (Kruschke & Meredith, 2018; Pedersen, 2017; Wickham et al., 2018), the `tidybayes` and `sjstats` packages for data analysis (Kay, 2018; Lüdecke, 2018), the `biosignalEMG` and `R.matlab` packages for signal processing (Bengtsson, 2016; Guerrero & Macias-Diaz, 2018), as well as the `glue` and `tidyverse` packages for code writing and formatting (Hester, 2017; Wickham, 2017).

Acknowledgements

This project was funded by the ANR project INNERSPEECH (grant number ANR-13-BSH2-0003-01). LN was funded by a PhD fellowship from Univ. Grenoble Alpes. We thank Nathalie Vallet for recording the relaxation sessions.

References

Alloy, L. B., Abramson, L. Y., Hogan, M. E., Whitehouse, W. G., Rose, D. T., Robinson, M. S., & Kim, R. S. (2000). The Temple-Wisconsin cognitive vulnerability to depression project: Lifetime history of Axis I psychopathology in individuals at high and low cognitive risk for depression. *Journal of Abnormal Psychology*, *109*(3), 403–418. https://doi.org/10.1037/0021-843X.109.3.403

Amit, E., Hoeflin, C., Hamzah, N., & Fedorenko, E. (2017). An asymmetrical relationship between verbal and visual thinking: Converging evidence from behavior and fMRI. *NeuroImage*, *152*, 619–627. https://doi.org/10.1016/j.neuroimage.2017.03.029

Aust, F., & Barth, M. (2018). *Papaja: Prepare reproducible apa journal articles with r markdown*. https://github.com/crsh/papaja

Bengtsson, H. (2016). *R.matlab: Read and write mat files and call matlab from within r*. https://CRAN.R-project.org/package=R.matlab

Bolinger, D. (1986). *Intonation and its parts*. London: Edward Arnold.

Bürkner, P.-C. (2018). *Brms: Bayesian regression models using 'stan'*. https://CRAN.R-project.org/package=brms

Carpenter, B., Gelman, A., Hoffman, M., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P., & Riddell, A. (2017). Stan: A probabilistic programming language.

Journal of Statistical Software, Articles, *76*(1), 1–32. https://doi.org/10.18637/jss.v076.i01

De Luca, C. J., Donald Gilmore, L., Kuznetsov, M., & Roy, S. H. (2010). Filtering the surface EMG signal: Movement artifact and baseline noise contamination. *Journal of Biomechanics*, *43*(8), 1573–1579. https://doi.org/10.1016/j.jbiomech.2010.01.027

Ehring, T., & Watkins, E. R. (2008). Repetitive negative thinking as a transdiagnostic process. *International Journal of Cognitive Therapy*, *1*(3), 192–205. https://doi.org/10.1680/ijct.2008.1.3.192

Fromkin, V. A. (1966). Neuro-muscular specification of linguistic units. *Language and Speech*, *9*(3), 170–199. https://doi.org/10.1177/002383096600900304

Ganis, G., Thompson, W. L., & Kosslyn, S. M. (2004). Brain areas underlying visual mental imagery and visual perception: An fMRI study. *Cognitive Brain Research*, *20*(2), 226–241. https://doi.org/10.1016/j.cogbrainres.2004.02.012

Gelman, A., Carlin, J. B., Stern, H., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2013). *Bayesian data analysis, third edition*. CRC Press, Taylor & Francis Group.

Goldwin, M., & Behar, E. (2012). Concreteness of idiographic periods of worry and depressive rumination. *Cognitive Therapy and Research*, *36*(6), 840–846. https://doi.org/10.1007/s10608-011-9428-1

Goldwin, M., Behar, E., & Sibrava, N. J. (2013). Concreteness of depressive rumination and trauma recall in individuals with elevated trait rumination and/or posttraumatic stress symptoms. *Cognitive Therapy and Research*, *37*(4), 680–689. https://doi.org/10.1007/s10608-012-9507-y

Grandchamp, R., Rapin, L., Perrone-Bertolotti, M., Pichat, C., Haldin, C., Cousin, E., Lachaux, J.-P., Dohen, M., Perrier, P., Garnier, M., Baciu, M., & Lœvenbruck, H. (2019). The ConDialInt Model: Condensation, Dialogality, and Intentionality Dimensions of Inner Speech Within a Hierarchical Predictive Control Framework. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.02019

Guerrero, J. A., & Macias-Diaz, J. E. (2018). *BiosignalEMG: Tools for electromyogram signals (emg) analysis*. https://CRAN.R-project.org/package=biosignalEMG

Hester, J. (2017). *Glue: Interpreted string literals*. https://CRAN.R-project.org/package=glue

Holmes, E. A., Mathews, A., Mackintosh, B., & Dalgleish, T. (2008). The causal effect of mental imagery on emotion assessed using picture-word cues. *Emotion*, *8*(3), 395–409. https://doi.org/10.1037/1528-3542.8.3.395

Hurlburt, R. T. (2011). *Investigating pristine inner experience: Moments of truth*. C. U. Press, Ed.

Jacobson, E. (1931). Electrical measurements of neuromuscular states during mental activities. VII. Imagination, recollection, and abstract thinking involving the speech musculature. *American Journal of Physiology*, *897*, 200–209.

Jeannerod, M. (2006). *Motor cognition: What actions tell the self*. Oxford University Press.

Johnson, D. P., & Whisman, M. a. (2013). Gender differences in rumination: A meta-analysis. *Personality and Individual Differences*, *55*(4), 367–374. https://doi.org/10.1016/j.paid.2013.03.019

Kapur, A., Kapur, S., & Maes, P. (2018). AlterEgo: A personalized wearable silent speech interface. *Proceedings of the 2018 Conference on Human Information*

Interaction&Retrieval - IUI '18, 43–53. https://doi.org/10.1145/3172944.3172977

Kay, M. (2018). *Tidybayes: Tidy data and geoms for mcmc/bayesian samplers.* https://github.com/mjskay/tidybayes

Kennedy, J. G., & Abbs, J. H. (1979). Anatomic Studies of the Perioral Motor System: Foundations for Studies in Speech Physiology. In N. J. Lass (Ed.), *Speech and Language* (Vol. 1, pp. 211–270). Elsevier. https://doi.org/10.1016/B978-0-12-608601-0.50009-7

Krahmer, E., & Swerts, M. (2004). More about brows: A cross-linguistic analysis-by-synthesis study. In Z. Ruttkay & C. Pelachaud (Eds.), *From brows to trust: Evaluating Embodied Conversational Agents*. Kluwer Academic Publishers.

Kruschke, J. K. (2015). *Doing Bayesian data analysis: A tutorial with R, JAGS, and Stan* (2nd Edition). Academic Press.

Kruschke, J. K., & Meredith, M. (2018). *BEST: Bayesian estimation supersedes the t-test.* https://CRAN.R-project.org/package=BEST

Laurent, L., Millot, J.-L., Andrieu, P., Camos, V., Floccia, C., & Mathy, F. (2016). Inner speech sustains predictable task switching: Direct evidence in adults. *Journal of Cognitive Psychology*, *8*(5), 585–592. https://doi.org/10.1080/20445911.2016.1164173

Lawrence, H. R., Haigh, E. A. P., Siegle, G. J., & Schwartz-Mette, R. A. (2018). Visual and verbal depressive cognition: Implications for the ruminationDepression relationship. *Cognitive Therapy and Research*, *42*(4), 421–435. https://doi.org/10.1007/s10608-018-9890-0

Lieshout Pascal H. H. M. van, Peters Herman F. M., Starkweather C. Woodruff, & Hulstijn Wouter. (1993). Physiological Differences Between Stutterers and Nonstutterers in Perceptually Fluent Speech. *Journal of Speech, Language, and Hearing*

Research, *36*(1), 55–63. https://doi.org/10.1044/jshr.3601.55

Livesay, J., Liebke, A., Samaras, M., & Stanley, A. (1996). Covert speech behavior during a silent language recitation task. *Perceptual and Motor Skills*, *83*, 1355–1362. https://doi.org/10.2466/pms.1996.83.3f.1355

Lüdecke, D. (2018). *Sjstats: Collection of convenient functions for common statistical computations*. https://CRAN.R-project.org/package=sjstats

Lyubomirsky, S., Caldwell, N. D., & Nolen-Hoeksema, S. (1998). Effects of ruminative and distracting responses to depressed mood on retrieval of autobiographical memories. *Journal of Personality and Social Psychology*, *75*(1), 166–177. https://doi.org/10.1037//0022-3514.75.1.166

Lœvenbruck, H. (2019). *Loquor, ergo communico-cognito-sum* [HDR]. Univ. Grenoble Alpes.

Lœvenbruck, H., Grandchamp, R., Rapin, L., Nalborczyk, L., Dohen, M., Perrier, P., Baciu, M., & Perrone-Bertolotti, M. (2018). A cognitive neuroscience view of inner language: To predict and to hear, see, feel. In P. Langland-Hassan & A. Vicente (Eds.), *Inner speech: New voices* (p. 37). Oxford University Press.

Maier-Hein, L., Metze, F., Schultz, T., & Waibel, A. (2005). Session independent non-audible speech recognition using surface electromyography. *IEEE Workshop on Automatic Speech Recognition and Understanding, 2005.*, 331–336. https://doi.org/10.1109/ASRU.2005.1566521

Marchetti, I., Mor, N., Chiorri, C., & Koster, E. H. W. (2018). The Brief State Rumination Inventory (BSRI): Validation and psychometric evaluation. *Cognitive Therapy and Research*, *42*(4), 447–460. https://doi.org/10.1007/s10608-018-9901-1

Martin, L. L., & Tesser, A. (1996). Some ruminative thoughts. In R. S. Wyer (Ed.), *Advances in social cognition, vol. 9* (Vol. 9, pp. 1–47). Hillsdale, NJ, US: Lawrence Erlbaum Associates, Inc.

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7

McGuigan, F. J., & Dollins, A. D. (1989). Patterns of covert speech behavior and phonetic coding. *The Pavlovian Journal of Biological Science*, *24*(1), 19–26.

McGuigan, F. J., & Winstead, C. L. (1974). Discriminative relationship between covert oral behavior and the phonemic system in internal information processing. *Journal of Experimental Psychology*, *103*(5), 885–890. https://doi.org/10.1037/h0037379

McLaughlin, K. A., Borkovec, T. D., & Sibrava, N. J. (2007). The effects of worry and rumination on affect states and cognitive activity. *Behavior Therapy*, *38*(1), 23–38. https://doi.org/10.1016/j.beth.2006.03.003

Meltzner, G. S., Sroka, J., Heaton, J. T., Gilmore, L. D., Colby, G., Roy, S., Chen, N., & Luca, C. J. D. (2008). Speech recognition for vocalized and subvocal modes of production using surface EMG signals from the neck and face. *INTERSPEECH*, 2667–2670.

Nalborczyk, L., Batailler, C., Lœvenbruck, H., Vilain, A., & Bürkner, P.-C. (2019). An introduction to Bayesian multilevel models using brms: A case study of gender effects on vowel variability in standard indonesian. *Journal of Speech Language and Hearing Research*, *62*(5), 1225–1242. https://doi.org/10.1044/2018_JSLHR-S-18-0006

Nalborczyk, L., Grandchamp, R., Koster, E. H. W., Perrone-Bertolotti, M., & Lœvenbruck, H. (2020). Can we decode phonetic features in inner speech using surface electromyography? *PLOS ONE*, *15*(5), e0233282. https://doi.org/10.1371/journal.pone.0233282

Nalborczyk, L., Perrone-Bertolotti, M., Baeyens, C., Grandchamp, R., Polosan, M., Spinelli, E., Koster, E. H. W., & Lœvenbruck, H. (2017). Orofacial electromyographic correlates of induced verbal rumination. *Biological Psychology*, *127*, 53–63. https://doi.org/10.1016/j.biopsycho.2017.04.013

Nalborczyk, L., Perrone-Bertolotti, M., Baeyens, C., Grandchamp, R., Spinelli, E., Koster, E. H. W., & Lœvenbruck, H. (2020). *Articulatory suppression effects on induced rumination* [Under Review].

Newby, J. M., & Moulds, M. L. (2012). A comparison of the content, themes, and features of intrusive memories and rumination in major depressive disorder: Intrusive memories and rumination. *British Journal of Clinical Psychology*, *51*(2), 197–205. https://doi.org/10.1111/j.2044-8260.2011.02020.x

Nicholls, M. E. R., Ellis, B. E., Clement, J. G., & Yoshino, M. (2004). Detecting hemifacial asymmetries in emotional expression with three-dimensional computerized image analysis. *Proceedings of the Royal Society B: Biological Sciences*, *271*(1540), 663–668. https://doi.org/10.1098/rspb.2003.2660

Nicholls, M. E. R., & Searle, D. A. (2006). Asymmetries for the visual expression and perception of speech. *Brain and Language*, *97*(3), 322–331. https://doi.org/10.1016/j.bandl.2005.11.007

Nolen-Hoeksema, S. (1991). Responses to depression and their effects on the duration of depressive episodes. *Journal of Abnormal Psychology*, *100*(4), 569–582. https://doi.org/10.1037//0021-843X.100.4.569

Nolen-Hoeksema, S., Wisco, B. E., & Lyubomirsky, S. (2008). Rethinking rumination. *Perspectives on Psychological Science*, *3*(5), 400–424. https://doi.org/10.1111/j.1745-6924.2008.00088.x

Papageorgiou, C., & Wells, A. (1999). Process and meta-cognitive dimensions of depressive and anxious thoughts and relationships with emotional intensity. *Clinical Psychology & Psychotherapy*, *6*(2), 156–162. https://doi.org/10.1002/(SICI)1099-0879(199905)6:2%3C156::AID-CPP196%3E3.0.CO;2-A

Pearson, M., Brewin, C. R., Rhodes, J., & McCarron, G. (2008). Frequency and nature of rumination in chronic depression: A preliminary study. *Cognitive Behaviour Therapy*, *37*(3), 160–168. https://doi.org/10.1080/16506070801919224

Pedersen, T. L. (2017). *Patchwork: The composer of ggplots*. https://github.com/thomasp85/patchwork

Perrone-Bertolotti, M., Rapin, L., Lachaux, J. P., Baciu, M., & Lœvenbruck, H. (2014). What is that little voice inside my head? Inner speech phenomenology, its role in cognitive performance, and its relation to self-monitoring. *Behavioural Brain Research*, *261*, 220–239. https://doi.org/10.1016/j.bbr.2013.12.034

Postma, A., & Noordanus, C. (1996). Production and detection of speech errors in silent, mouthed, noise-masked, and normal auditory feedback speech. *Language and Speech*, *39*(4), 375–392. https://doi.org/10.1177/002383099603900403

Radloff, L. S. (1977). The CES-D Scale: A Self-Report Depression Scale for Research in the General Population. *Applied Psychological Measurement*, *1*(3), 385–401. https://doi.org/10.1177/014662167700100306

R Core Team. (2018). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Robinson, M. S., & Alloy, L. B. (2003). Negative cognitive styles and stress-reactive rumination interact to predict depression: A prospective study. *Cognitive Therapy and Research*, *27*(3), 275–292. https://doi.org/10.1023/A:1023914416469

Schultz, T., & Wand, M. (2010). Modeling coarticulation in EMG-based continuous speech recognition. *Speech Communication*, *52*(4), 341–353. https://doi.org/10.1016/j.specom.2009.12.002

Simmons, J., Nelson, L., & Simonsohn, U. (2012). A 21 word solution. *The Official Newsletter of the Society for Personality and Social Psychology*, *26*(2). https://doi.org/10.2139/ssrn.2160588

Smith, J. M., & Alloy, L. B. (2009). A roadmap to rumination: A review of the definition, assessment, and conceptualization of this multifaceted construct. *Clinical Psychology Review*, *29*(2), 116–128. https://doi.org/10.1016/j.cpr.2008.10.003

Sokolov, A. (1972). *Inner speech and thought*. Springer-Verlag.

Tan, J.-W., Walter, S., Scheck, A., Hrabal, D., Hoffmann, H., Kessler, H., & Traue, H. C. (2012). Repeatability of facial electromyography (EMG) activity over corrugator supercilii and zygomaticus major on differentiating various emotions. *Journal of Ambient Intelligence and Humanized Computing*, *3*(1), 3–10. https://doi.org/10.1007/s12652-011-0084-9

Treynor, W., Gonzalez, R., & Nolen-Hoeksema, S. (2003). *Rumination reconsidered : A psychometric analysis*. *27*(3), 247–259. https://doi.org/10.1023/A:1023910315561

van Boxtel, A., & Jessurun, M. (1993). Amplitude and bilateral coherency of facial and jaw-elevator EMG activity as an index of effort during a two-choice serial reaction task. *Psychophysiology*, *30*(6), 589–604. https://doi.org/10.1111/j.1469-8986.1993.tb02085.x

Wagenmakers, E.-J., Lodewyckx, T., Kuriyal, H., & Grasman, R. (2010). Bayesian hypothesis testing for psychologists: A tutorial on the SavageDickey method. *Cognitive Psychology*, *60*(3), 158–189. https://doi.org/10.1016/j.cogpsych.2009.12.001

Waterink, W., & van Boxtel, A. (1994). Facial and jaw-elevator EMG activity in relation to changes in performance level during a sustained information processing task. *Biological Psychology*, *37*(3), 183–198. https://doi.org/10.1016/0301-0511(94)90001-9

Watkins, E. R., Moulds, M. L., & Mackintosh, B. (2005). Comparisons between rumination and worry in a non-clinical population. *Behaviour Research and Therapy*, *43*(12), 1577–1585. https://doi.org/10.1016/j.brat.2004.11.008

Watkins, E. R., & Nolen-Hoeksema, S. (2014). A habit-goal framework of depressive rumination. *Journal of Abnormal Psychology*, *123*(1), 24–34. https://doi.org/10.1037/a0035540

Wickham, H. (2017). *Tidyverse: Easily install and load the 'tidyverse'*. https://CRAN.R-project.org/package=tidyverse

Wickham, H., Chang, W., Henry, L., Pedersen, T. L., Takahashi, K., Wilke, C., & Woo, K. (2018). *Ggplot2: Create elegant data visualisations using the grammar of graphics*. https://CRAN.R-project.org/package=ggplot2

Woody, A., Smolak, E. L., Rabideau, E. M., Figueroa, W. S., & Zoccola, P. M. (2015). Trait rumination moderates the effect of mentation type on heart rate responses to stressor recall. *Stress*, *18*(5), 554–560. https://doi.org/10.3109/10253890.2015.1055726

Xie, Y. (2018). *Knitr: A general-purpose package for dynamic report generation in r*. https://CRAN.R-project.org/package=knitr

Zoccola, P. M., Rabideau, E. M., Figueroa, W. S., & Woody, A. (2014). Cardiovascular and affective consequences of ruminating on a performance stressor depend on mode of thought: Mode of rumination, blood pressure and anxiety. *Stress and Health*, *30*(3), 188–197. https://doi.org/10.1002/smi.2588