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Understanding rumination as a form of inner speech

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RÉSUMÉ

To be detailed...

OVERZICHT

To be detailed...

ABSTRACT

To be detailed...

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PREFACE

This PhD has been realised as a joint PhD between Univ. Grenoble Alpes (Grenoble, France) and Ghent University (Ghent, Belgium). It has been funded by Univ. Grenoble Alpes (UPMF)...

The underlying code as well as an online version of this thesis is available at: https://github.com/lmalborczyk/phd_thesis.

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Part I

Theoretical chapters

THEORETICAL FRAMEWORK

Inner speech is nothing but speech to oneself
Sokolov, A. N. (1972)

As you read these words, you might notice the presence of an inner voice accompanying your reading. This phenomenon usually remains unnoticed until we pay attention to it. However, if I ask you to focus on that little voice while you are reading these lines, you would probably be able to provide a relatively fine-grained description of this thing that we call inner speech. Whose voice is it? Is it yours? Is it gendered? It is usually possible to examine these aspects as well as its lower-level features such as its tone, pitch, tempo, or virtually any sensory aspect of it. This first set of very basic observations already provide us some very important insights. First, if we can think about inner speech, then it should be something different from thinking itself. Rather, inner speech (or *covert speech*) can be construed as a vehicle for conscious thought¹. Second, the set of observations we can make about our inner voice also tautologically reveals that inner speech is accompanied by sensory percepts (e.g., speech sounds, kinaesthetic feelings). It thus raises another set of fascinating questions about the origin and nature of inner speech percepts. Where do these percepts come from? Why do they look like the one we experience when we speak overtly?

This first set of questions refer to the *nature* of inner speech, that is, to *what* it is. In the present work, we are mostly concerned with this question. Another set of issues revolve around the question of the *functions* of inner speech, that is, *what it is for*. The influential Vygotskian theory of inner speech development suggests that inner speech evolves from *private speech* (i.e., self-addressed overt speech) during childhood. As such, we (as others have argued elsewhere) assume that the functions of inner speech are inherited from the functions of private speech, via a mechanism of progressive internalisation. The specific features of this internalisation process are worthy of investigation on their own (and we

¹We will not delve into the touchy question of whether inner speech is a necessary condition for consciousness. For the present work purpose, it is sufficient to note that thinking and inner speech are phenomenologically separable.

briefly discuss them later on) but we are mostly interested here in the *what is* (i.e., the nature) question. Thus, we will only sparsely address the question of the functions of inner speech.

That being said, a lot can be learned about inner speech by looking at situations in which these functions do not work as intended. These *dysfunctions* are instances of inner speech when its (functional or adaptive) functions, such as problem-solving, self-regulation or planning (we discuss these in more details later) do not work as intended. These dysfunctionnal instances of inner speech may include auditory verbal hallucinations (AVH; for a detailed investigation of the relation between inner speech and AVHs, see Rapin, 2011), where the sense of agency (i.e., whose the author of the internal speech) is impaired, or repetitive negative thinking such as worry or rumination, where the ability to control (or to disengage) from negative thoughts is impaired. In the present work, we investigated (some of) the psychophysiological correlates of rumination, starting with the theoretical assumption that rumination can be considered as a form of inner speech. Therefore, we studied rumination as we would study another form of inner speech, with the potential of refining the conceptualisation of both rumination and inner speech.

Rumination is associated with increased risks in the onset and maintenance of several psychiatric disorders such as the major depressive disorder (MDD) or the generalised anxiety disorder (GAD) []. Societal importance of depression and anxiety... However, although rumination has mainly been studied in the framework of depression and anxiety, it has been shown to be a key process in more than thirteen disorders []. Therefore, rumination can generally be understood as transdiagnostic processes (i.e., a process that is not specific to a single pathology). The term of rumination...

In this first chapter, we briefly review the main theoretical frameworks in which rumination has been studied. We then review the historical and contemporary conceptualisations of inner speech and suggest how rumination can be considered (and studied) as a form of inner speech. We then broaden the discussion by considering the analogy between inner speech and the broader phenomenon of motor imagery. Finally, we discuss how electromyography can be used (and has been used) to investigate covert actions, before moving to a brief introduction to the technical aspects of the present work (Chapter 2).

1.1 Rumination as a form of repetitive negative thinking

1.1.1 Theoretical perspectives on rumination

For review, see Smith & Alloy (2009), Nolen-Hoeksema, Wisco, & Lyubomirsky (2008), and Watkins (2008)...

One of the most prolific model of rumination is the Response Style Theory (RST; Nolen-Hoeksema, 1991a). Accoring to this theory, rumination consists of repetitive thinking about the causes, consequences and symptoms of negative affects...

This theory has been later appended... stress-reactive model of rumination, in which ruination occur after a stressful event. It has the advantage of explaining how rumination can appear in reaction to stressful events (even before the apparition of negative affects)...

The Goal Process Theory (Martin & Tesser, 1996) conceptualises rumination as a response to a failure to achieve (or to progress toward) a certain goal....

The Self-Regulatory Executive Function (S-REF) model of rumination...

Watkins model...

The cognitive approach (Koster, De Lissnyder, & De Raedt, 2013; Koster, De Lissnyder, Derakshan, & De Raedt, 2011)... from the RST to control theories and the mental habit theory...

As suggested by Christoff, Irving, Fox, Spreng, & Andrews-Hanna (2016), rumination and other forms of spontaneous thoughts can be considered in a common conceptual space (see Figure 1). This space is built upon two dimensions: *deliberate constraints* and *automatic constraints*. These dimensions represent two general mechanisms that allow to constrain the contents of these related mental states and the transitions between them. The first constrain correspond to a deliberate process and is implemented through **cognitive control** (Miller, 2000). The second constrain is referring to more automatic constrains like sensory afferences. In this framework, rumination is characterised by the highest level of automatic constraints and spread all along the *deliberate constraints* dimension.

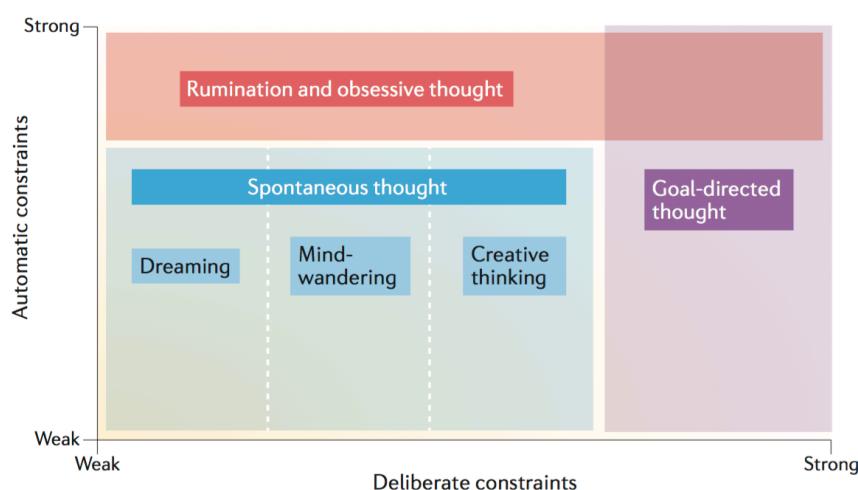


Figure 1.1: Conceptual space of different types of thought (Christoff et al., 2016)

...

1.1.2 Measures of rumination

Behavioural measures (questionnaires, and cognitive tasks), and physiological measures (HRV, stress)...

1.1.3 On the verbal and sensory properties of rumination

...

1.2 What is that little voice inside my head ?

1.2.1 Brief historical overview of inner speech investigations

Description, functions, nature...

Soviet psychology... marxist psychology... Akhutina (2003) highlights a distinction between the study of inner speech (and speech production in general) in the west based

on linguistics and chomsky work, and its origin in marxist psychology in the east, where language is to be thought in relation to its usages...

Vygostky essential properties of inner speech: i) abbreviation, the phonetic aspect is “diminished”, reduced, “In inner speech we do not need to pronounce a word in its entirety. We understand, by virtue of our very intention, what word we wanted to say... Strictly speaking, inner speech is almost wordless” (Vygotsky, 1956, p. 368). ii) predicativeness, “Psychologically, inner speech consists of predicates only”; “the subject of our inner reason is always present in our thought”; it is always implicitly understood (Vygotsky, 1956, pp. 364, 365), iii) it has a semantic structure of its own: predominance of *sense* over *meaning*², it is idiomatic, agglutination of semantic units, etc.

Therefore, for Vygostky, it follows that the passage from inner speech to overt speech consists not in simply “vocalising” inner speech but in *restructuring* inner speech (e.g., retrieving a syntax proper to overt speech, retrieving the phonetic structure, etc)...

In the last chapter of this book, Vygotsky analyzes the relationship between thought and word in the mature mind. The central idea of this chapter is stated as follows:

The relationship between thought and language is not a thing, but a process, a continual movement back and forth from thought to word and from word to thought. Viewed in the light of a psychological analysis, this relation is a process that passes through a series of phases and stages, during which its essential features undergo changes that may be called development in the strict sense. Of course, this is a functional development, not development in the sense of aging; but the path traversed by thinking as a process from thought to word is development nonetheless.

Vygotsky ends this statement with his famous dictum: *Thought is not expressed in words; it comes into existence through them* (1956, p. 330)...

²this refers to Paulhan's distinction between the dictionary *meaning* of a word on one hand, and the individual *sense* (meaning) of a word, acquired by usage, on the other hand.

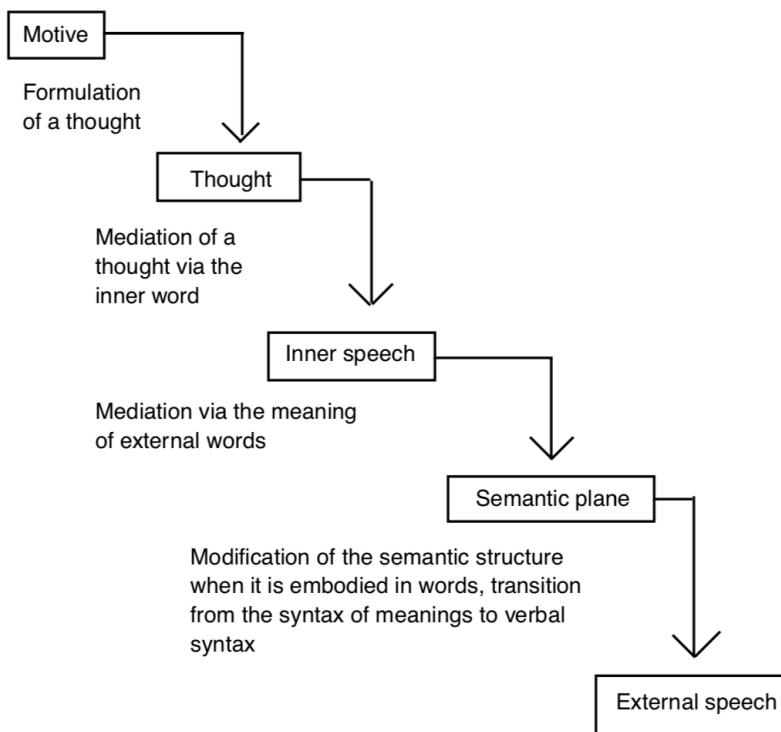


Figure 1.2: Vygotskys Levels in the Process of Verbal Thinking. Figure from Akhtuina (2003).

For Luria (1956), a verbal utterance usually starts with a *motive*³, that is something to express. For Luria, a verbal utterance always starts with a *vague thought* and the role of inner speech would be to transform this thought into speech. Three stages i) the motive ii) the thought and its transformation to inner speech and iii) transformation to external speech... in his studies of aphasia, Luria (1947) then recognises that each of these stages can be (more or less) independently impaired....

Copy-pasted from Akhutina (2003): The way was paved for this hypothesis by Soviet psychology and its notion of the multilevel structure of inner speech (Anan'ev, 1946, 1960; Sokolov, 1959, 1968). In Anan'ev's view, one of the indisputable postulates of inner-speech theory is "that inner speech is a process that varies in terms of its readiness to be transformed into external speech." For Anan'ev, inner speech has the following phases...

Watson (1919) suggested that thought was rooted in (overt) speech, with maturation leading from speech to thought.. this hypothesis also applied to reading, with beginning reader overtly reading and progressively silently reading...

See Reed 1916 for an historical perspective... this initial suggestion (by Watson) lead to a fruitful line of research about the muscular bases and/or correlates of thought and inner speech... for instance, Reed (1916) observed that participants were moving their tongue and lips (and sometimes whispering) while reading...

In a small monograph, Stricker (1880) reported that... however, Paulhan (1886) replied that he was able to produce (innerly) the vowel 1 and maintain the image of other vowels and that he was able to imagine the sound of any vowel without motor actions or feelings (images). Maybe this debate illustrates the limitations of the introspective method... which gives birth to experimental methods at the beginning of the last century... for instance Reed (1916) describes an apparatus to examine tongue movements (see Figure XX) and an

³This includes desires and needs, interests and impulses, affects and emotions, etc.

experiment to examine the involvement of inner speech (and speech motor processes) in thinking...

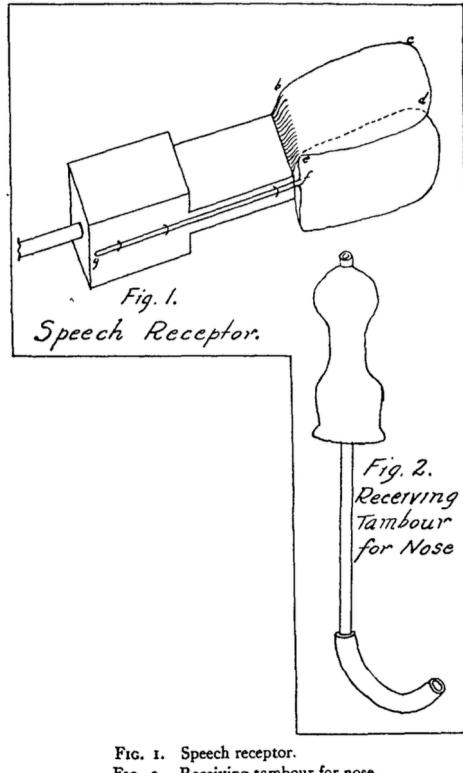


FIG. 1. Speech receptor.
FIG. 2. Receiving tambour for nose.

Figure 1.3: Figure 1 & 2 from Reed (1916), describing the apparatus used to record tongue movement during thinking and inner speech.

Faaborg-Anderson and Edfeldt (1958) found that activity in vocal musculature increased with difficulty of text (see also Sokolov, 1972)... however it is not clear that reading always entails inner speech and (or more precisely), that inner speech always involve “sub-articulation”... discuss counter-examples by the “anesthesists” (e.g., Smith, Brown, Toman, & Goodman, 1947)...

Historical perspective on the exploration of the role of motor processes in inner speech, from Sokolov (1972). Dodge (1898) anesthetised his lips and tongue and realised that this impact on his inner speech. Curtis (1899) and Courten (1902) recorded laryngeal movements using a pneumatic drum and a kymograph while his participants recited verses or were reading. They observed that laryngeal movement were not always present and depended on what was being read and/or produced, as well as on the “degree of understanding”...

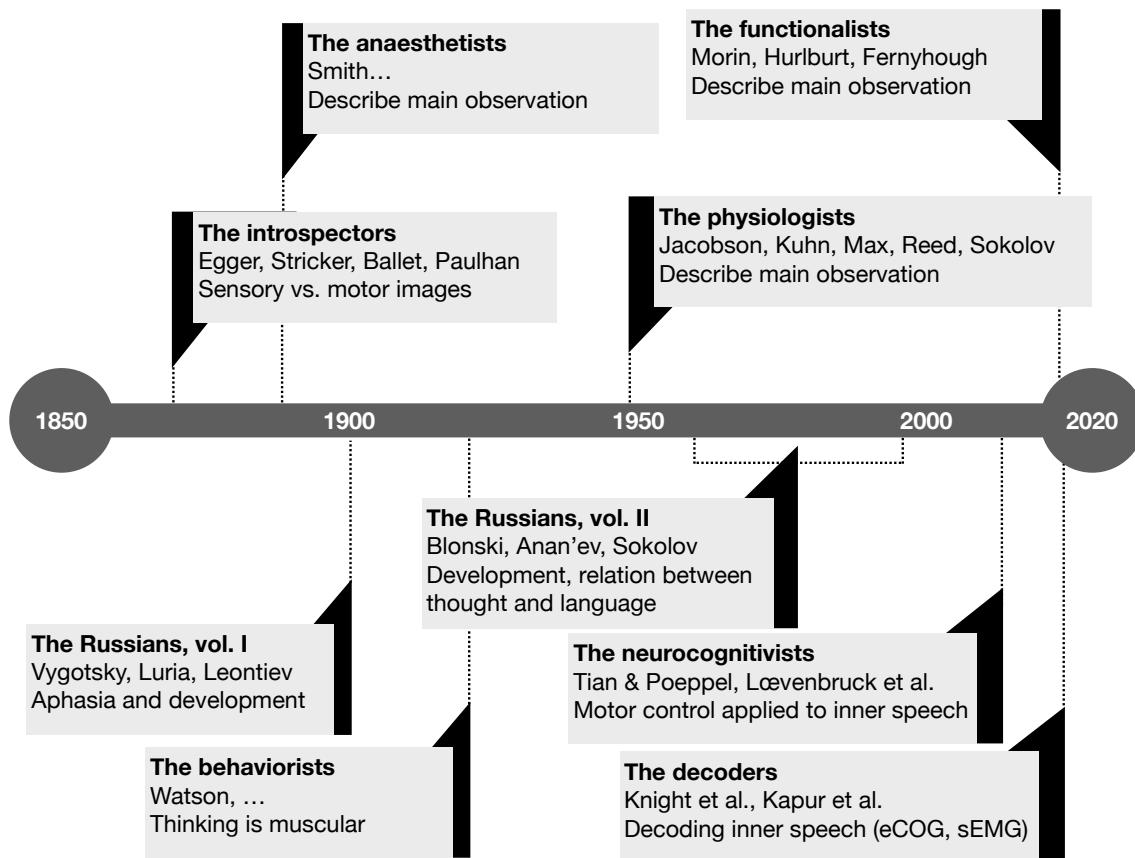


Figure 1.4: Non-exhaustive overview of contemporary inner speech research from 1850 to present days.

Jacobson (1931) used a galvanometer to record action potentials of tongue and lips muscles and observed small muscles contraction during inner speech production, “as if words were pronounced in a rapid and abbreviated manner” (cited in Sokolov, 1972, p. 45).

The discussion of inner speech in soviet Psychology resolved mostly around the issue of the functions of inner speech. The work of Lev Vygotsky and PP Blonsky (for instance) culminated in suggesting that inner speech is speech “to oneself” and “for oneself”. Interestingly, Vygotsky rejected both the verbal memory view of inner speech (i.e., inner speech is simply the retrieval of acoustic, optic or motor images of words) and the behaviourist view of inner speech as merely a soundless form of external speech (à la Watson). For Vygotsky, the most determining factors of inner speech are its semantic features...

Concerning the development of inner speech, Vygotsky considered that inner speech likely derives from the *egocentric speech*⁴ of the preschool child. This lead Vygotsky to claim a functional equivalence between egocentric speech and internal speech, the latter resulting from a progressive internalisation of the former...

Vygotsky... high *predicativeness* of inner speech (no subject), because we know what we are talking about... abbreviateness...

Sokolov (1972) provided seminal observations that inner speech is involved during reading, to an extent that is directly related to the difficulty of the ongoing reading task. More

⁴According to Piaget, the egocentric speech is a conversation of the child aloud with herself.

precisely, he observed that the more difficult the task was, the stronger the “speech motor impulses” (EMG amplitude) in the speech muscles. Moreover, the difficulty of the task was also related to the abbreviateness of inner speech. Simpler reading tasks were associated with abbreviated (condensed) inner speech whereas difficult tasks were associates with “unfolded” (expanded) inner speech, and sometimes externalised (overt) speech... Sokolov (1972) also show shown that, reciprocally, restrictiing the articulators of the participants (e.g., by clamping the tongue or lips) impaired the ability of the participants to complete the task...

On the rate of inner speech as compared to overt speech, see Anderson (1982), Mackay (1981)...it would be 15% to 20% faster than overt speech (Coltheart, 1999)...

1.2.2 Theoretical perspectives about inner speech production

The inner voice as the sensory consequence (prediction, see Loevenbruck et al., 2018) of imagined speech. Analogy with raising the arm: what we perceive when we imagine raising our arm are the sensory consequences (e.g., visual) of what would happen if we actually raised our arm, these are then kind of predictions. The same thing happens during inner speech production: the inner voice is the predicted auditory consequence of actual speech, except that it's predicted. The two actions might seem very different, partly because of differences in the degree of automaticity. Imagining raising our arm might need a voluntary/deliberate/conscious (choose a word) intention (i.e., I want to raise my arm > I raise my arm) while speech imagery (i.e., inner speech) seems more automatic: we do not expression consciously the intention to speak, we just speak...

Argument about phonological activation during reading, see Abramson & Goldinger (1997), cited in Ehrich (2006)... inner speech seems most prominent in beginning readers, or when processing difficult texts (Coltheart, Besner, Jonasson, & Davelaar, 1979)...

Abramson & Goldinger (1997) investigated the vowel-length effect (i.e., the fact that the length of the produced vowel depend on the surrounding consonants) was present in inner speech...they shown (in a lexical decisin task) that the response time was slowr to long-vowel stimuli than to short-vowel stimuli...but they do note, interestingly, that heir data do not indicate that inner speech is “*necessayr* for reading; it may simply be epiphenomenal” (Abramson & Goldinger, 1997, p. 1066)...

Huey (1968) proposed that phonological representations during reading were auditory...he propsoed that reading involves some form of auditory imagery, the voice in the head (or *inner hearing*)...he explained that this voice becams more and more abbreviated (and therefore less auditorily sailliant) as reader become more skilled (as explained in Abramson & Goldinger, 1997)...in the same vein, Stricker (1880) prposed that (silent) reading was impossible without movements of larynx and lips...

1.2.2.1 The working memory perspective

...Baddeley (1986) introduces in his model the osbvocal rehearsal component, whose role is to prevent decay in short term memory. This tripartite model comprise one central exectuvie system and two slave systems. Within these slaves systes, verbal information is rehearsed within the phonological store throuhg a meachnism know as the phonological loop, acting to prevent memory loss in short term memory or working memory...

...whereas studies have shown that children can store verbal information, the active (silent) rehearsal of verbal information seems somehow “deficient” before the age of 7 years

(e.g., Flavell, Beach, & Chinsky, 1966)... which is coherent with the Vygotskian predictions discussed earlier...

... recent attempt to integrate the verbal working memory and language literatures... Buchsbaum & D'Esposito (2019)...

1.2.2.2 MVTV Cohen (1986)

...

1.2.2.3 Predictive models

...

Speech production involves the fine-grained coordination of more than 100 muscles in the upper part of the body (Simonyan & Horwitz, 2011). In adult humans, its covert counterpart (i.e., *inner speech* or *verbal imagery*) has developed to allow the full reconstruction of usual overt speech situations. In the same way as visual imagery allows to mentally examine visual scenes, *verbal imagery* can be used as an internal tool, allowing –amongst other things– to rehearse or to prepare past and future speech situations (for a review, see Perrone-Bertolotti, Rapin, Lachaux, Baciu, & Lvenbruck, 2014). In consideration of its self-evident motoric nature, a parallel can be drawn between verbal imagery and other forms of motor imagery (e.g., imagined walking or imagined writing). As such, inner speech studies might benefit from insights gained from the study of motor imagery and the field of motor cognition (e.g., Haggard, 2005; Jeannerod, 2006).

The process of speech internalisation might be similar the internalisation of any kind of motor action. Considering inner speech as any other form of motor action brings some interesting insights. If speech production can be broadly described as the coordinated motion of (groups of) muscles that result in some predictable sensory consequences (e.g., auditory, visual, kinesthetic or somesthetic feelings), then it can be compared to other forms of action. In that sense, the process of speech internalisation, as the process of “internalised walking”, might follow the same general steps. This process can be broadly defined as the learning of the mapping between some muscular command or patterns of muscular commands and the associated sensory consequences. Learning these associations result in the elaboration of an internal model of the mapping, that permit to predict ongoing actions, but also to simulate these actions in the absence of any overt movement. In that sense, the process of inner speech might be considered under the broad category of imagined actions...

Let's consider the analogy between speaking and playing an instrument (e.g., the piano). Learning how to play piano can be reduced to the learning and coordination of complex and fine motor sequences, that in turn produce sensory (kinesthetic, auditory, visual, etc) feedback to the producer of the action (the agent). It seems that (from a certain level of analysis), the act of speech can be paralleled with the act of playing an instrument in that it consists in the coordination of infinitely complex movements that result in some modifications in the environment, that in turn generate sensory feedbacks for the agent. Thus, pursuing the analogy, we could argue that imagining playing an instrument and imagining speaking (i.e., producing inner speech) might rest on similar mechanisms (e.g., see O'Shea & Moran, 2018).

This view is somehow consistent with the Vygotskian view of inner speech as internalised egocentric (or private) speech but it proposes a formal mechanism to explain it...

1.2.2.4 Loevenbruck et al., HMOSAIC

...

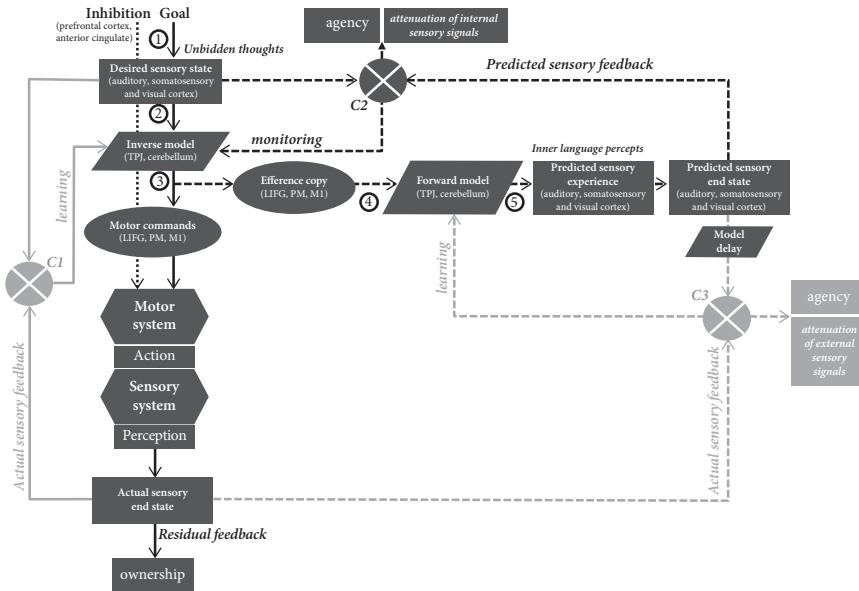


Figure 1.5: Predictive control account of inner speech production. Figure from Loevenbruck et al. (2018).

1.2.2.5 Action representation and internal models

Voir Jeannerod (1994) and Wolpert, Ghahramani, & Jordan (1995), Wolpert & Gharamani (2000)...

Box 1.1: What is an internal model ?

Blah blah...

...

1.3 Theoretical perspective on motor imagery

Considerable experimental evidence has accumulated to suggest that movement execution and motor imagery share substantial overlap of active brain regions (for review, see Guillot, Di Rienzo, MacIntyre, Moran, & Collet, 2012). Such apparent functional equivalence supports the hypothesis that motor imagery draws on the similar neural networks that are used in actual perception and motor control (Grzes & Decety, 2001; Jeannerod, 1994)...

See introduction of O'Shea (2017) PhD thesis introduction... See Stinear's chapter in Guillot's book for intracortical and spinal mechanisms involved during motor imagery (p.55-57).

1.3.1 Overt and imagined actions

Wittgenstein's (1953) famous query: "When I raise my arm, what is left after subtracting the fact that my arm raised?". We posit that what is left is an internal model (a representation) of what should happen if and when my arm goes up (Jeannerod, 1999)...

1.3.2 The motor simulation theory

In his seminal paper, Jeannerod (1994) introduces the idea of a close functional equivalence between motor imagery and motor preparation, as suggested by the similar neural and physiological correlates observed in both imaging and preparing (and by the effects of motor imagery on motor learning and training). According to Jeannerod, actions are driven by an "internally represented world rather than directly by the external world" (page 187). In the next paragraph(s), Jeannerod seems to equate motor representations with motor images or what he calls *pragmatic representations* (page 187). For Jeannerod, motor imagery is a part of a broader phenomenon (the motor representation) related to intending and preparing movements (page 189). He also echoes the distinction (coming from sport psychology) between *internal* (imagining an action from the first perspective, which would be more kinesthetic) and *external imagery* (imagining an action from the third perspective, which would be more visual). For him, motor imagery necessarily belongs to the former type (page 189), whereas the term of *motor imagery* in sport psychology seems to more broadly encompass both first-person and third-person motor imagery [e.g.,].

Motor preparation is unconscious while motor imagery is conscious. However, Jeannerod suggests that the difference between the two might be a difference of degree, rather than one of kind, as the difference between the two would only be determined by the time spent on each (i.e., if one makes motor preparation lasting for longer than it's usually needed, it can "become" motor imagery, page 190). In plain words, the idea is that motor representations/intentions become known to the subject when they are not followed by execution (page 190), so there would be a continuum between motor preparation and motor imagery.

EMG lines of evidence page 191: Eye movements have been recorded during the recall of visual scenes (e.g., Jeannerod & Mourat 1962). Jacobson (1930) first suggested that muscles were selectively activated during imagined action. Shaw (1940) reported that during imagined weight lifting, electromyographic (EMG) activity of forearm muscles increased linearly with the magnitude of the weight, etc.

Neural structures and physiological correlates page 192-193.

Evidence from mental chronometry and temporal equivalence (e.g., Landauer, 1962), showing that it takes approximately the same amount of time to say the alphabet or series of numbers aloud and to think them to himself.

The famous walking + load experiment of Decety, Jeannerod, & Prablanc (1989) reveals that force, rather than duration, is the encoded variable, and that estimated duration is merely derived from the level of centrally represented force. When the subjects carried the load, they centrally programmed a greater force to overcome any resistance, because subjects did not actually walk (page 194). For Jeannerod, the programming of force as a subjective correlate: the sensation of effort, which can become perceptible to the actor independently of overt movement execution and can be monitored experimentally (page 194). Page 196: representation of kinematic regularities (e.g., Fitts' law, Viviani's experiments, etc.).

In the following (section 5, starting page 197), Jeannerod develops the idea that the goal of an action includes an internal representation of both the external object toward which it is directed and the final state of the organism when that object has been reached. Then, he develops on the idea of a distinction between a pragmatic mode and a semantic mode (page 198). He also makes a distinction between two functions of representations: a sensory one (to extract from the external world the attributes of objects or situations that are relevant to a given action) and a motor one (to encode some aspects of that action) (page 199).

NB: in this paper (Jeannerod, 1994), there is no explicit mention of a “simulation” process... Jeannerod only discusses the conscious access to the content of a representation, and defines it as motor imagery (cf. notes above as well as the distinction drawn by Grush, 2004). Interestingly, in the commentaries, Morton suggests that many of the cases Jeannerod reports are actually instances of simulations, rather than mere imagination, because these cases contain part of what would be involved in actual performance (page 215). In his response, Jeannerod seems to agree with and to endorse this view (e.g., page 231).

In the commentary of this paper Gursh suggests that... (Motor models as steps to higher cognition (Rick Grush)) there should exist an inverse model, and points that nothing mentioned in the target article is actually capable of generating mental imagery. For Grush, this inverse model would act centrally, taking as input the efferent copy (for instance) and would output a mock version of the afferent signals the peripheral system would have produced given the same input (i.e., an emulator, see page 209).

For Jeannerod (1995), motor imagery is necessarily first-perspective. Third perspective imagery is imagery, but not MOTOR imagery... Motor representations are conceived here as ‘internal models’ of the goal of an action.

In Jeannerod (2001), “Covert and overt stages thus represent a continuum, such that overtly executed action implies the existence of a covert stage, whereas a covert action does not necessarily turn out into an overt action” (page S103). Jeannerod introduces the term S-states to designate mental states which involve an action content and where brain activity can be shown to simulate that observed during the same, executed, action. These S-states correspond to intended action, imagined action, and many others (see Table 1, page S104).

In Jeannerod (2006), The Simulation Hypothesis of Motor Cognition (pages 129-164). See Schematic summary of motor simulation according to Jeannerod (page 133).

“Simulation is used here as the off-line rehearsal of neural networks involved in specific operations such as perceiving or acting (page 129). According to our view [...], the simulation relates not to complete actions but to unspecific elements that comprise actions. Motor representations are automatically assembled in response to immediate task requirements and do not rely on memorized actions (page 134).”

The peripheralist versus centralist interpretation of physiological inner speech correlates (page 153): Subvocal speech was first interpreted as a source of peripheral kinesthetic information which, when projected to central nervous structures, generated auditory images of the corresponding words. The same interpretation was given to the low intensity EMG recorded during mental motor imagery of limb actions, which was thought to be the origin of the feelings experienced by the subject during mental rehearsal (Jacobson 1930), or to the eye movements recorded during mental visual imagery (e.g. Brandt and Stark, 1997). However, this interpretation of mental processes as consequences of peripheral feedback is now disproved by recent experiments showing complete absence of muscular activity in many subjects during motor imagery. When present, this activity is rather assumed to be a consequence of incomplete inhibition of motor output during

mental states involving motor simulation. This same interpretation might also hold for inner speech.

Motor imagery can be defined as the mental process by which one rehearses a given action, without engaging in the physical movements involved in this particular action. One of the most influential theoretical explanation of this broad phenomenon, the *motor simulation theory* (MST, Jeannerod, 1994, 2001, 2006), contains the three following postulates at its core: i) there exists a continuum between the covert (the mental representation) and the overt execution of an action, ii) action representations can operate off-line, via a *simulation* mechanism, and iii) covert actions rely on the same set of mechanisms as the overt actions they simulate, except that execution is inhibited (O'Shea & Moran, 2017).

In this framework, the concept of simulation refers to the “offline rehearsal of neural networks” (Jeannerod, 2006), and motor imagery is conceptualised as a simulation of the covert stage of the same executed action (O'Shea & Moran, 2017). The MST shares some similarities with the theories of embodied and grounded cognition (Barsalou, 2008) in that both allow to account for the phenomenon of motor imagery by appealing to a simulation mechanism. However, the concept of simulation in grounded theories is assumed to be multi-modal (not just motoric) and to operate in order to achieve a particular abstract knowledge (O'Shea & Moran, 2017), which is not the concern of the MST⁵.

The MST is supported by a wealth of findings, going from mental chronometry studies showing that the time taken to perform an action is often found to be similar to the time needed to imagine the corresponding action (though not always, see Glover & Baran, 2017, for a review of controversial findings and for an alternative conceptualisation of motor imagery), to neuroimaging and neurostimulation studies showing that both motor imagery and overt actions tend to recruit similar frontal, parietal and sub-cortical regions (e.g., Hétu et al., 2013; Jeannerod, 2001). The involvement of the motor system during motor imagery is also supported by repeated observations of autonomic responses and peripheral muscular activity during motor imagery (we discuss these observations in section XX).

⁵We should also make a distinction between *embodiment of content*, which concerns the conceptual content of language, and *embodiment of form*, which concerns “the vehicle of thought”, that is, proper speech production (Pickering & Garrod, 2013).

Box 1.2: Centralism versus peripheralism

The motor theory of perception: mental states arise from movement (more precisely, from innervation associated with movements (the perceived image of an object arises from the muscular discharges produced during the movements involved in exploring it). The peripheral variant of the motor theory is the idea according to which the mental image of that object is also produced by covert muscular discharges in the related muscles (cf. work from James, 1890; Jacobson, 1930).

But the idea developed in this paper is quite the reverse of the peripheral motor theory and would be more akin to a centralist version of the motor theory (page 190). Jeannerod says that existence of muscle discharge during a mental state does not imply a bottom-up influence of these discharges on the mental state. The key phenomenon in Jeannerods conception is the motor intention, which is though to be largely endogenous (page 190). Motor imagery would represent the results of conscious access to the content of the intention, and the content of the intention would constrain the expression of the image (page 190). Jeannerod also states that this view is in agreement with the corollary discharge model. The key idea is that the activation of peripheral mechanisms is not needed to generate the image (but they can be activated, as a consequence of the activation of the image/representation)...

1.3.3 Emulation and internal models

NB: in this paper emulator is used as a synonym for “forward models” (pages 378-379)...

Grush (2004) proposes a unified framework for explaining a wide variety of representational functions of the brain: the emulation theory of representation. This theory has its origins in control theory (forward models) and signal processing (Kalman filters).

Difference between emulation theory of motor imagery and simulation theory à la Jeannerod (pages 384-385): “[...] Given these definitions, it should be clear that the simulation theory and the emulation theory are not at all the same thing. They agree that the efferent motor centers are active during imagery. The simulation theory takes this by itself to be sufficient for motor imagery; the emulation theory does not, and claims that in addition, an emulator of the musculoskeletal system is needed and imagery is produced when the efferent motor centers drive this emulator. This distinction should be entirely obvious. To make an analogy: The emulation theory claims that motor imagery is like a pilot sitting in a flight simulator, and the pilot’s efferent commands (hand and foot movements, etc.) are translated into faux “sensory” information (instrument readings, mock visual display) by the flight simulator which is essentially an emulator of an aircraft. The simulation theory claims that just a pilot, moving her hands and feet around but driving neither a real aircraft nor a flight simulation, is sufficient for mock sensory information.”

Distinguishing between simulation and emulation theories (page 385): “[...] The only way to get from the former (signals in motor format) to the latter (signals in proprioceptive and kinesthetic format) is to run the motor signal through something that maps motor plans/signals to proprioception and kinesthesia. And the two possibilities are (a) the body (yielding real proprioception and kinesthesia), and (b) a body emulator (yielding faux proprioception and kinesthesia) [...] A motor plan is one thing, a sequence of

proprioception and kinesthesia is another. The simulation theorist conflates them.”

In Moulton & Kosslyn (2009), In brief: they tried to characterize mental imagery as an information processing system, considering it in the perspective of Marr’s three levels of explanation (i.e., the computational, algorithmic, and implementation levels).

Imagery is also characterized by its reliance on perceptual representations and activation of perceptual brain systems. We use this conception of imagery to argue that all imagery is simulation— more specifically, it is a specific type of simulation in which the mental processes that ‘run’ the simulation emulate those that would actually operate in the simulated scenario. This type of simulation, which we label emulation, has benefits over other types of simulations that merely mimic the content of the simulated scenario. They note (page 1273): “[...] ‘motor imagery’ (which actually appears to be proprioceptive or kinaesthetic imagery—one experiences the bodily sensations of movement, not the movement commands themselves: Jeannerod, 1994).”

A second class of explanatory models of motor imagery are concerned with the phenomenon of *emulation* and with *internal models* (see Gentsch, Weber, Synofzik, Vosgerau, & Schütz-Bosbach, 2016, for a review of the similarities and dissimilarities of simulation and emulation models).

Internal model theories share the postulate that the motor system is represented by *internal models*, whose function is to estimate and anticipate the outcome of a motor command. One of its variant, the *motor control theory* (e.g., Kawato, 1999; Wolpert et al., 1995), assumes two kind of models: a forward model that predicts the sensory consequences of motor commands from efference copies, and an inverse model that calculates the feed-forward motor commands from the desired movement (Gentsch et al., 2016).

Emulation theories (e.g., Grush, 2004; Moulton & Kosslyn, 2009) borrow from both previously discussed framework (i.e., simulation theories and internal model theories) to posit a specific kind of simulation. While the MST postulates that during simulation the motor system is guided exclusively by internal motor representations, the emulation theories suggest that both motor and sensory systems are emulated in parallel (Grush, 2004; O’Shea & Moran, 2017).

In the emulation model proposed by Grush (2004), the *emulator* is a device that implements the same input-output function as the body (i.e., the musculoskeletal system and relevant proprioceptive/kinaesthetic systems). When the emulator receives a copy of the control signal (which is also sent to the body), it produces an output signal (the emulator feedback), identical or similar to the feedback signal produced by the body⁶. This feedback would be responsible for the presence of sensory percepts (e.g., visual, auditory, kinaesthetic) during motor imagery.

One important difference between the emulation theory of motor imagery and the MST though, is that the latter takes the mere activation of efferent motor centres as being sufficient for explaining motor imagery, while the emulation theory postulates that an emulator of the musculoskeletal system is needed (Grush, 2004, pp. 384–385). Grush (2004) suggested an analogy to illustrate this difference: “The emulation theory claims that motor imagery is like a pilot sitting in a flight simulator, and the pilot’s efferent commands (hand and foot movements, etc.) are translated into faux “sensory” information (instrument readings, mock visual display) by the flight simulator which is essentially an emulator of an aircraft. The simulation theory claims that just a pilot, moving her hands and feet around but driving neither a real aircraft nor a flight simulation, is sufficient for mock

⁶In Grush’s terminology, *emulator* is used as a synonym for *forward models* (see Grush, 2004, pp. 378–379).

sensory information". Alternatively, in the words of Moulton & Kosslyn (2009), instrumental simulations (à la Jeannerod) can be thought of as *first-order* simulations that imitate the content of the simulated action, while emulative simulations can be thought of as *second-order* simulations that imitate both the content and the processes that change the content.

1.4 Electromyography of covert actions

1.4.1 Explaining the muscular activity during motor imagery

Motor imagery has consistently been defined as the mental rehearsal of a motor action without any overt movement. One consequence of this claim is that, in order to prevent execution, the neural commands for muscular contractions should be blocked at some level of the motor system by active inhibitory mechanisms (for a review, see Guillot et al., 2012). Despite these inhibitory mechanisms, there is now abundant evidence for peripheral muscular activation during motor imagery (for a review, see Guillot & Collet, 2005; Guillot et al., 2012). As suggested by Jeannerod (1994), the incomplete inhibition of the motor commands would provide a valid explanation to account for the peripheral muscular activity observed during motor imagery. This idea has been corroborated by studies of changes in the excitability of the motor pathways during motor imagery tasks. Bonnet, Decety, Jeannerod, & Requin (1997) measured spinal reflexes while participants were instructed to either press a pedal with the foot or to simulate the same action mentally. They observed that both H-reflexes and T-reflexes increased during motor imagery, and that these increases correlated with the force of the simulated pressure. Using transcranial magnetic stimulation and motor evoked potentials (MEPs), several investigators observed muscle-specific increases of MEPs during various motor imagery tasks, while no such increase could be observed in antagonist muscles (e.g., Fadiga et al., 1999; Rossini, 1999)⁷.

Box 1.3: The motor inhibition problem

The problem of inhibition (page S106): how come that covert actions, in spite of activation of the motor system, do not result in muscular activity and overt movements? Two possibilities:

- * Subliminal activation during S-states, insufficient to fire spinal motoneurons
- * Or, activations would be blocked/attenuated before to reach the motoneurons by an inhibitory mechanism generated in parallel to the motor activation...

NB: these two possibilities are not necessarily incompatible...

Interestingly, the dominant interpretation of the muscular correlates of motor imagery at the beginning of the last century was that the peripheral muscular activity observed during imagined actions was the *source* of the mental content. However, as explained by Jeannerod (2006), this interpretation of mental processes as a consequence of peripheral feedback is now disproved, for instance by the simple fact that many people can experiment

⁷As a side note, we should remark that these findings are consistent with both the simulation and the emulation views on motor imagery.

motor imagery, without any observable muscular activity⁸. In the most recent theoretical explanations of motor imagery (e.g., MST, emulation or internal models theories), the peripheral activity is rather assumed to be a consequence of an incomplete inhibition of motor output during the mental states involving motor simulation/emulation (i.e., these views adhere to a *centralist* interpretation of the physiological correlates of inner speech).

1.4.2 Controversial findings

As reviewed in Guillot, Lebon, & Collet (2010), although there are many observations showing a peripheral muscular activity during motor imagery, there are also many studies failing to do so, or reporting surprisingly high levels of inter-subject variability, with some participants showing no muscular activity at all. Putting aside the discussion on the exact nature and location of the inhibitory mechanisms during motor imagery (see Guillot et al., 2012), two main explanations have been advanced to resolve these discrepancies. First, the electromyographic activity recorded during motor imagery could be moderated by the perspective taken in motor imagery. We usually make a distinction between a first-person perspective or *internal imagery* (i.e., imagining an action as we would execute it) and a third-person perspective or *external imagery* (i.e., imagining an action as an observer of this action), that seem to involve different neural and cognitive processes. It has been shown that a first-person perspective generally results in greater EMG activity than motor imagery in a third-person perspective (Hale, 1982; Harris & Robinson, 1986). Second, some authors postulated that the intensity of the EMG activity recorded during motor imagery might be related to the individual ability to form an accurate mental representation of the motor skill (i.e., the vividness of the mental image). However, after reviewing the available evidence, Guillot et al. (2009) concluded that this is unlikely to be the case. Alternatively, discrepancies in experimental design and methodological choices (e.g., use of intramuscular versus surface electromyography) could also explain these different results (Guillot et al., 2010).

In the next section, we turn to a discussion of inner speech conceptualised as a kind of motor (and sensory) imagery of speech, and discuss the theoretical underpinnings of this proposition as well as the available empirical evidence in its support.

1.4.3 Electromyographic correlates of inner speech production

Various terms: internal speech, silent speech, covert speech, implicit speech, speech imagery... difference between generative component (mackay, 1992) / inner speaking / inner voice and perceptual or auditory component (MacKay, 1992) or inner hearing / inner ear...

A key question: what is the lowest level of specification of inner speech ? ... figure from oppenheim & dell (2010...)

See MacKay (1992, page 131) for discussion of speaking rate in inner and overt speech... faster rates also occur for other highly trained skills (e.g., tying a shoelace, Annett, 1988)... ref to review of Guillot...

⁸The *peripheralist* interpretation has also been disproved by the heroic experiment carried out by Smith et al. (1947). Smith used d-tubocurarine (curare) to paralyse his own facial muscles in order to test this interpretation. He later reported that, while being paralysed, he was still able to think in words and to solve mathematical problems.

EMG during inner speech (from mckay, 1992): “interestingly, this same EMG activity invariably precedes by a few milliseconds the full blown muscle activity that occurs during normal movements” (e.g., Schmidt, 1982)…

Box 1.4: Proper control conditions in electromyographic studies of inner speech production

Guidelines from Garrity (1977) here...

While grasping the concept of a visual image appears as relatively straightforward, it seems more difficult at first to grasp the concept of a motor image, especially when it comes to verbal imagery. The subjective experience of the tension that results from a given position of the articulators and the covert production of an incompatible speech sound permits to substantiate what a motor image is. For instance, it is generally impossible to generate the image of the pronunciation of the sound “b” while keeping the mouth wide opened (e.g., Binet, 1886; Stricker, 1880). This simple experiment allows defining imagined speech as the simulation of the corresponding overt verbal content, where *simulation* is meant to be understood either as the off-line rehearsal of neural motor networks involved in the overt action (Jeannerod, 2006), or in the terms of the emulation theories discussed previously⁹.

The model of wilful (voluntary) inner speech production introduced in Lvenbruck et al. (2018) goes one step further and, by building on the models of speech motor control (e.g., Houde & Nagarajan, 2011; Wolpert et al., 1995), describes inner speech as “multi-modal acts with multi-sensory percepts stemming from coarse multi-sensory goals”. In other words, the auditory and kinaesthetic sensations perceived during inner speech prediction are assumed to be the predicted sensory consequences of speech motor acts, emulated by internal forward models, that use the efference copies issued from an inverse model (this proposal shares similarities with the emulation model of motor imagery discussed earlier, Grush, 2004).

Fin de l'intro old de zygote...

In other words, “inner speech is nothing but speech to oneself” (Sokolov, 1972)... it can be considered as a n internalisation, a psychological transofmration or “internal projection” of overt speech (Sokolov, 1972)...

⁹Translated to speech, the MST is similar to previous proposals such as the *motor theory of voluntary thinking* (Cohen, 1986) or the hierarchical model of mental practice (Mackay, 1981).

METHODOLOGICAL FRAMEWORK

In this chapter we briefly introduce some of the key concepts related to the methods we used in our work. More precisely, we cover the technical concepts related to speech production mechanisms, to electromyography and to our statistical approach. Finally, we give an overview of the following chapters.

2.1 Speech production mechanisms

2.1.1 Psychological aspects of speech production

How do we (humans) produce speech ? At a biomechanical level, producing speech means coordinating a complex dynamic system (i.e., the ensemble of speech muscles and organs) to produce slight perturbations of the air flow (sound waves). At a psychological level, speech production can be said to consist in the translation of thoughts into speech, with the goal of communicating information. Before being communicated however, the information of interest is submitted to several important transformations.

Although speech production is an everyday phenomenon, the way this process is exactly performed is still the subject of lively debates. However, current models generally agree with the core steps occurring during speech production. Willem Levelt (Levelt, 1989, 2000) proposed an influential psycholinguistic model of speech production (see Figure 2.1). According to this model, speech production can be described at three levels: *conceptualisation*, *formulation* and *articulation*. The first step is managed by a component called the *conceptualizer*, and consists in selecting a conceptual message to be produced (*message generation*). In other words, the speaker conceives a communicative intention that she wishes to reveal to an interlocutor. This *preverbal message* is then forwarded to another component, the *formulator*, that handles both *grammatical encoding* (i.e., selecting the appropriate word or *lemma*) and *phonological encoding* (i.e., selecting the appropriate speech sounds).

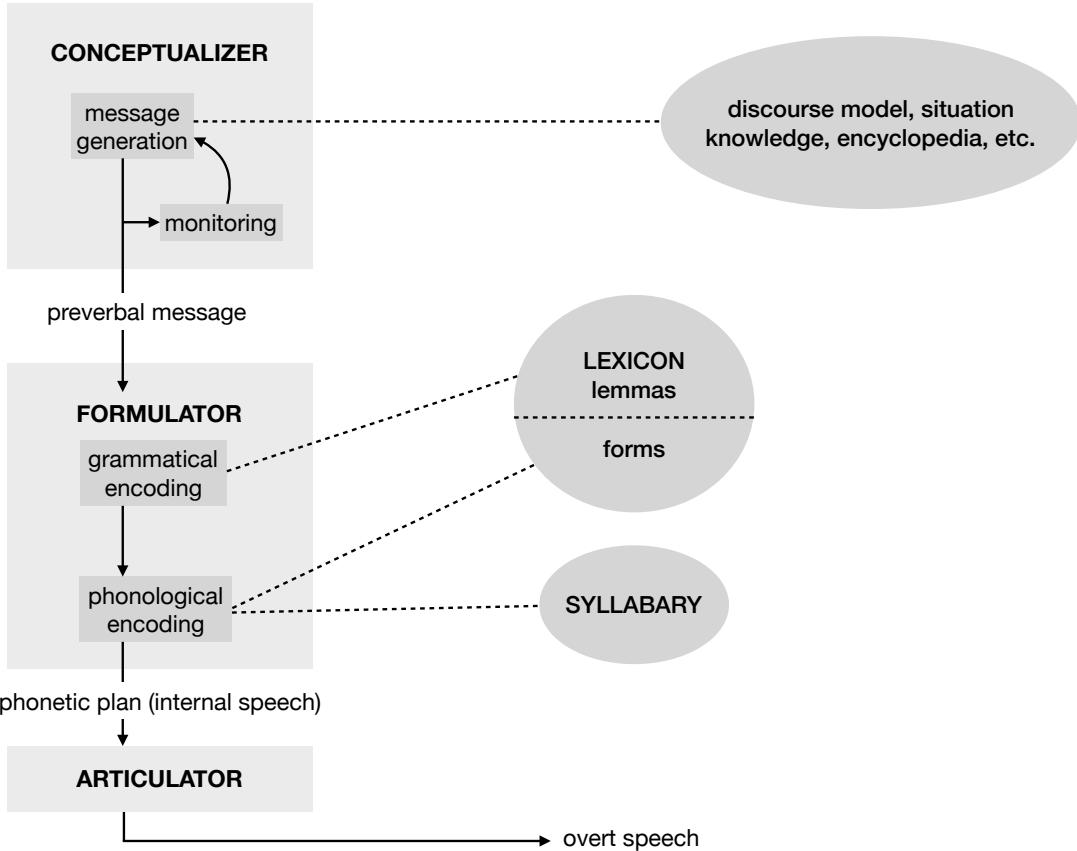


Figure 2.1: Illustration of Levelt's (1989, 2000) model of speech production.

During *grammatical encoding*, *lemmas* are retrieved from the *lexicon* and are ordered in a syntactical appropriate way, giving the message its *surface structure*. During *phonological encoding*, the message is given its phonetic or articulatory characteristics. At this stage, phonemes are grouped into pronounceable syllables. Then, each syllable is associated with an *articulatory program*, composed of an ensemble of *articulatory gestures* (i.e., coordinative structures of movements). These articulatory programs are stored in the *syllabary*. In brief, the *formulator* component transforms a *preverbal message* into a linguistic object. Finally, the *phonetic plan*¹ is forwarded to the *articulator*, responsible for the activation of *articulatory gestures*, to be executed by the speech *articulators* (e.g., tongue, lips, jaw).

This model permits to explain how a communicative intention is transformed into speech acts. However, it does not explicitly account for how speech acts are executed by the articulators. In the next section, we briefly introduce some of the cores principles related to the biomechanics of speech production.

2.1.2 Biomechanical aspects of speech production

2.1.2.1 Vocal apparatus

Speech production requires the involvement of more than 100 muscles in the face, the neck and the chest (Simonyan & Horwitz, 2011). The activity of these muscles is coordinated

¹Interestingly, in this model the phonetic plan is thought to correspond to inner speech.

to produce an air flow moving from the lungs to the oral and nasal cavities, via the trachea, the larynx and the pharynx (see Figure 2.2). Broadly speaking, speech production can be said to consist essentially in i) *phonation*, which refers to the manipulation of the air flow and to the vibration of the vocal folds and ii) *articulation*, which refers to movements of the *articulators*. The action of the *articulators* (e.g., lips, tongue) is to shape the oral and nasal cavities, resulting in modifications of the sound waves and in the production of different vowels.

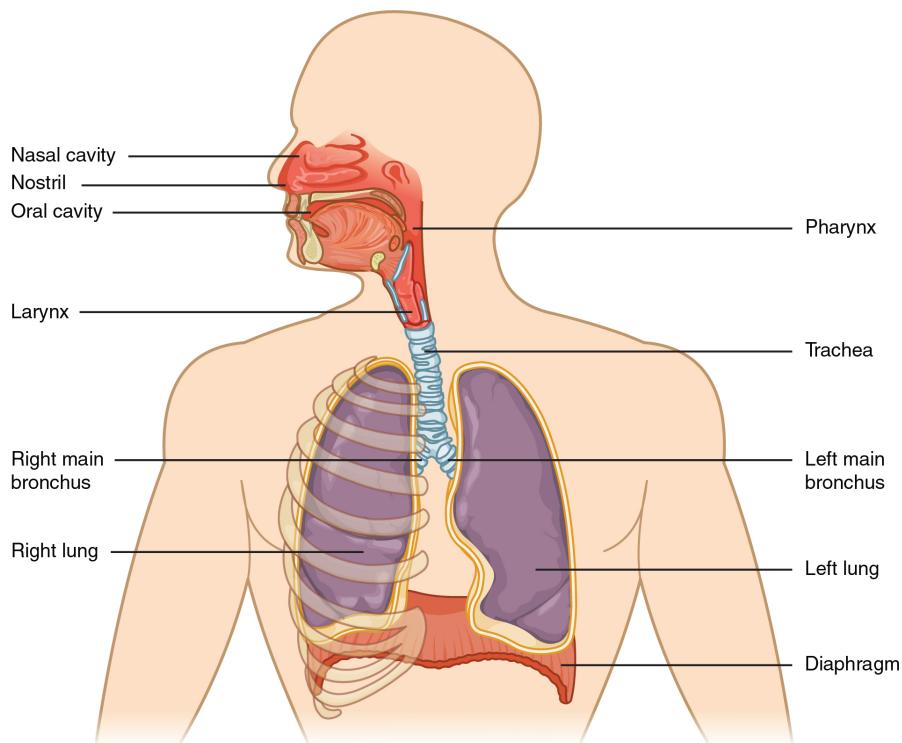


Figure 2.2: Human respiratory and phonatory system. Figure from the OpenStax Anatomy and Physiology Textbook. Download for free at <http://cnx.org/contents/14fb4ad7-39a1-4eee-ab6e-3ef2482e3e22@15.1>.

The characteristics of the vocal folds (e.g., their length or thickness) influence what is known as the *fundamental frequency* (or F0) of the speech signal, which in turn determines the perceived pitch of the voice. The speech signal can be further decomposed in *resonant frequencies* or *formants*. Interestingly, we can relate changes in the state of the articulatory system with changes in the formant (and especially the F1-F2) space (see Figure 2.3). Indeed, the frequency of the first formant (F1) is mostly determined by the height of the tongue body whereas the frequency of the second formant (F2) is mostly determined by the frontness/backness of the tongue body. For instance, when producing the /u/ vowel, the tongue is positioned at the top and in the back of the oral cavity (and the lips are rounded). However, when producing the /a/ vowel, the tongue is positioned at the bottom of the oral activity (and the lips are widely opened).

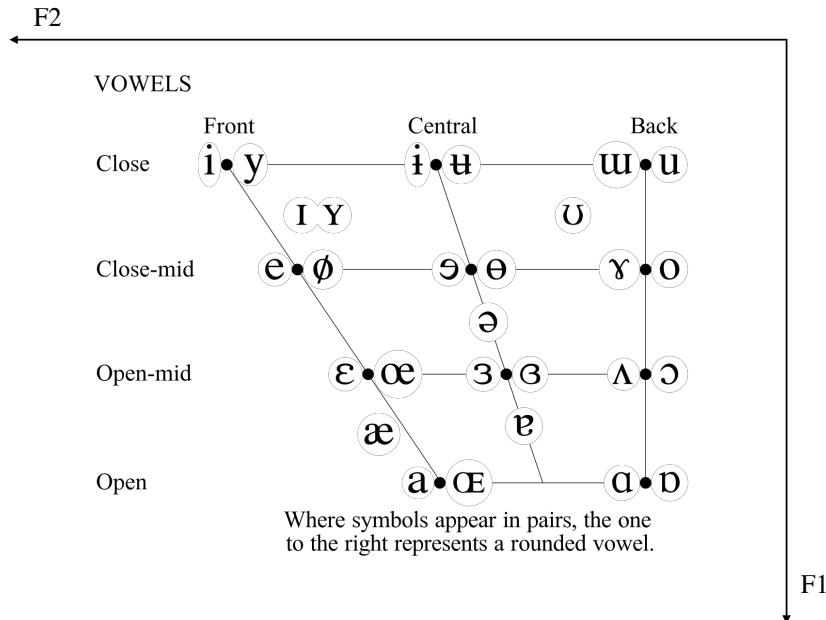


Figure 2.3: Illustration of the vocalic 'quadrilateral' and the relation between vowels and formants (F1 and F2). Figure adapted from the International Phonetic Association (2015) - IPA Chart, available under a Creative Commons Attribution-Sharealike 3.0 Unported License.

In brief, modifications in the shape of the *vocal tract* result in the production of different vowels. Changes in the configurations of articulators such as the lips or the tongue may also produce consonants. Consonants are produced by applying some form of restriction to (or by closing) the vocal tract to constraint the air flow. We usually classify consonants according to *where* (the *place of articulation*) and *how* (the *manner of articulation*) this restriction takes place (see Figure 2.4). For instance, consonants such as /p/ or /b/ are produced by putting the lips together and are therefore known as *bilabial* consonants.

CONSONANTS (PULMONIC)											© 2015 IPA	
	Bilabial	Labiodental	Dental	Alveolar	Postalveolar	Retroflex	Palatal	Velar	Uvular	Pharyngeal	Glottal	
Plosive	p b			t d		t ð	c ɟ	k g	q ɣ			?
Nasal	m	m̪		n		ɳ	ɲ	ŋ	N			
Trill	B			r					R			
Tap or Flap		v̪		r̪		ʈ̪						
Fricative	ɸ β	f v	θ ð	s z	ʃ ʒ	ʂ ʐ	ç ɟ	x ɣ	χ ʁ	ħ ʕ	h ɦ	
Lateral fricative			ɬ ɺ									
Approximant		v̪		ɹ̪		ɻ̪	ɺ̪	ɻ̪	ɻ̪			
Lateral approximant			l̪		ɻ̪	ɺ̪	ɻ̪	ɻ̪	ɻ̪			

Symbols to the right in a cell are voiced, to the left are voiceless. Shaded areas denote articulations judged impossible.

Figure 2.4: Table of consonants according to the manner (in rows) and place (in columns) of articulation. Figure from the International Phonetic Association (2015) - IPA Chart, available under a Creative Commons Attribution-Sharealike 3.0 Unported License.

To sum up, besides from being an essential communication tool for humans, speech production is also a complex motor action, involving the fine-grained coordination of numerous muscles. In the next section, we discuss in more details the specific facial muscles that were of interest in the present work.

2.1.2.2 Orofacial speech muscles

In our work, we were especially interested in the activity of some of the orofacial muscles (i.e., the muscles situated around the mouth). More precisely, we studied the activity of the *orbicularis oris inferior* (OOI), the *orbicularis oris superior* (OOS), and the *zygomaticus major* (ZYG) muscles (cf. Figure 2.5). Contrary to what was assumed until recently, the *orbicularis oris* muscle is not a sphincter muscle but is instead a complex of several distinct muscles that interlace in a way that gives the *orbicularis oris* complex its circular aspect. Among these muscles, the OOS and the OOI are placed above and below (respectively) the mouth and are responsible for rounding or protruding the lips. More precisely, the OOS is responsible for lowering the upper lip whereas the OOI is responsible for elevating the lower lip. The ZYG muscle has its origin on the zygomatic bone and inserts at the labial commissure (the angle of the mouth) where it meets with fibers of the *levator anguli oris* and *orbicularis oris* muscles. Together with the *levator anguli oris*, it serves to move the labial commissure upwards and laterally, and is involved in laughing and more generally in pleasant reactions and positive emotions. It is also involved in speech production, especially during the production of *spread* sounds, that is, sounds that require a wide aperture of the mouth (e.g., /i/).

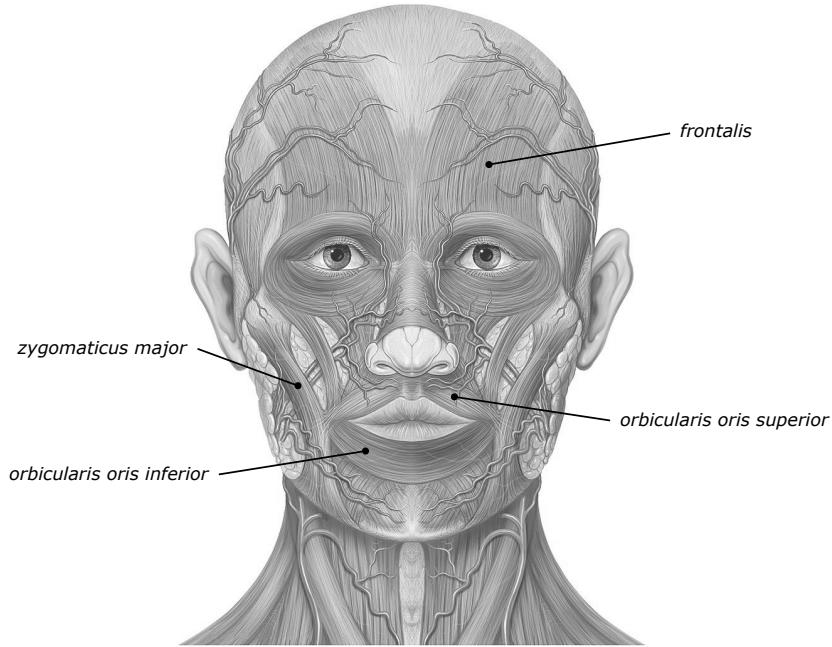


Figure 2.5: Illustration of the main facial muscles of interest in the present work. Figure adapted from Patrick J. Lynch, medical illustrator, <http://patricklynch.net>.

For sensors placement, we followed guidelines and recommendations from Fridlund & Cacioppo (1986). In addition to speech-related orofacial muscles, we also routinely recorded the activity of other facial muscles such as the *frontalis* muscle (FRO) in Chapter 3, 4, 5,

and the *corrugator supercilii* muscle (COR) in Chapter 5. The activity of these muscles was monitored to control for non speech-related facial muscular activity (as recommended by Garrity, 1977).

There are several ways to probe the involvement of specific articulators in a given speech production task. For instance, it is possible to selectively interfere with the activity of some articulators (or groups of articulators) to demonstrate their essential involvement in this particular task. It is also possible to record the activity of facial muscles peripherally using surface electromyography, without interfering with (or with minimal interference to) the natural course of the speech production process. In the next section, we briefly introduce some core concepts of electromyography.

2.2 A brief introduction to electromyography

Technically speaking, electromyography (EMG) is an experimental technique concerned with the recording and analysis of myoelectric signals (i.e., signals resulting from physiological variations in the state of muscle fibers membranes). Broadly speaking, EMG is a measure of the electrical activity generated during muscle contraction. It is used both as a basic tool in (for instance) biomechanical and psychophysiology research and as an evaluation tool in applied research (e.g., physiotherapy, rehabilitation, human-computer interfaces). To facilitate the interpretation of the EMG signal, it is useful to briefly detail the meaning of its physiological components.

2.2.1 Nature of the EMG signal

2.2.1.1 Muscular anatomy and physiology

A muscle is a collection of fibers that can vary in length, orientation, diameter, and architectural characteristics. For instance, deeper muscle fibers are usually composed of a greater proportion of slow-twitch fibers (type I muscle fibers) whereas more superficial muscle fibers comprise a greater proportion of larger and fast-twitch fibers (type II muscles fibers, Kamen & Gabriel, 2010). On the basis of their structure and contractile properties, we can identify three types of muscle tissues: i) the *skeletal muscles* are attached to bones, their function is to produce voluntary movements and to protect the organs, ii) the *cardiac muscles*, whose function is to pump blood and iii) the *smooth muscles*, involved in involuntary movements (e.g., respiration, moving food).

The contraction of the skeletal muscles is initiated by electrical impulses that propagate from the central nervous system to the muscle via the α -motoneurons. Interestingly, many (both larger and smaller) muscles are partitioned, with each portion having a specific role for the muscle function. Moreover, there is no one-to-one mapping between populations of motor neurons and muscle compartments. In other words, one population of motoneurons may innervate several compartments and reciprocally, several populations of motoneurons may innervate the same muscle compartment. Therefore, interpreting the EMG signal requires to be aware whether the recorded signal is characteristic of a whole muscle' activity or of a specific muscle compartment (Kamen & Gabriel, 2010).

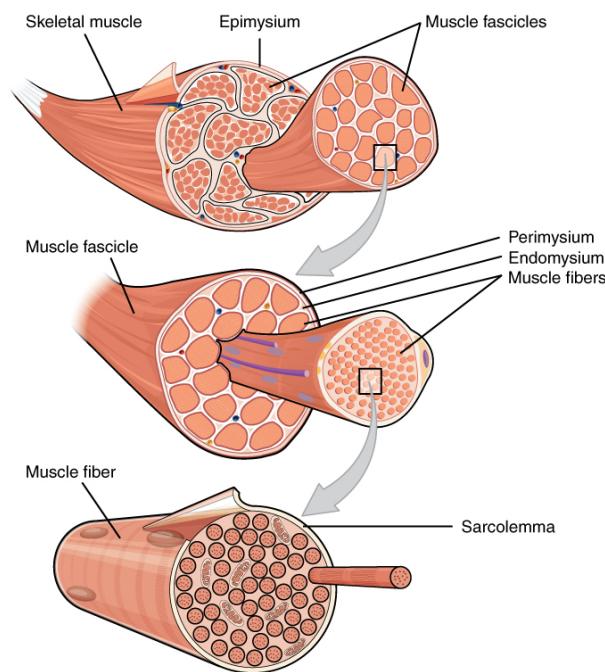


Figure 2.6: Illustration of a muscle fiber. Figure from the OpenStax Anatomy and Physiology Textbook. Download for free at <http://cnx.org/contents/14fb4ad7-39a1-4eee-ab6e-3ef2482e3e22@15.1>.

The muscle fiber is surrounded by a membrane, the *sarcolemma* (see Figure 2.6). Under resting conditions, the voltage inside the membrane is around -90mV, relative to the outside. This voltage results from a particular combination of sodium (Na^+), potassium (K^+), chloride (Cl^-), and other anions. At rest, the concentration of Na^+ is relatively high outside the membrane and relatively low inside the membrane. The concentration of K^+ follows an opposite pattern, with a greater concentration inside the membrane, and a lower concentration outside the membrane.

2.2.1.2 The motor action potential

Because muscle membranes can change their electrical state, muscle fibers are excitable tissues. When a muscle fiber is depolarised, the *membrane potential* produces a response called the *muscle fiber action potential* or more generally the *motor action potential* (MAP). The generated action potential proceeds along the muscle fiber in both directions from the neuromuscular junction (Kamen & Gabriel, 2010)². In the first phase of the MAP, the Na^+ permeability increases dramatically, inducing a massive income of Na^+ into the cell. This results in a temporary inversion of the cell polarity (see Figure 2.7).

²The *neuromuscular junction* is the site where the motoneuron meets the muscle fiber.

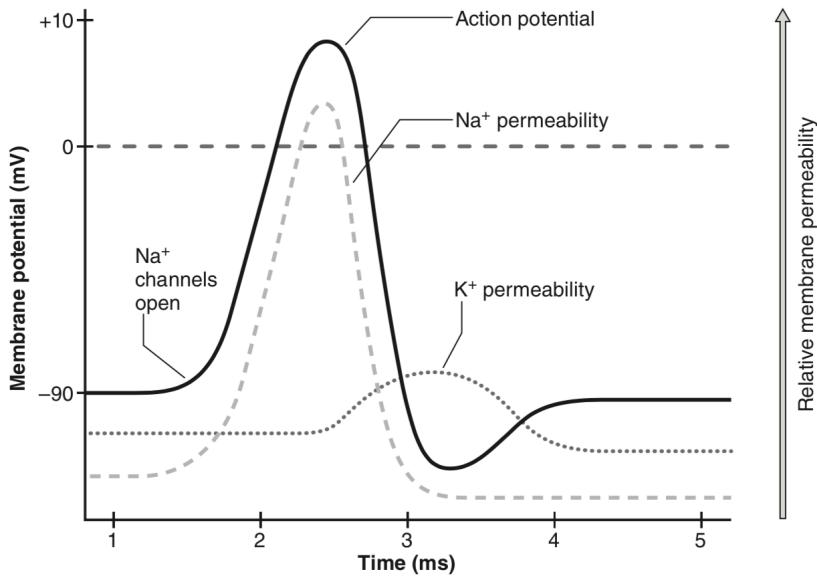


Figure 2.7: Time course of a motor action potential (figure from Kamen & Gabriel, 2010).

The MAP is followed by a *refractory period*, characterised by a decrease in membrane excitability. This refractory period can be further decomposed in an *absolute* refractory period during which all Na^+ channels are closed, and a *relative* refractory period where some Na^+ channels are open (but to a lesser extent than before the MAP). Interestingly, this after-impulse hyperpolarisation limits the frequency of MAPs (Kamen & Gabriel, 2010).

2.2.1.3 The motor unit

The *motor unit* is the smallest controllable muscular unit. It consists in a single α -motoneuron, its neuromuscular junction, and all the muscle fibers it innervates. The number of motor units and their *innervation ratio* (i.e., the number of muscle fibers per motor unit) can vary by muscle. Because a single motoneuron can innervate multiple muscle fibers, the firing of a single motoneuron results in the simultaneous discharge of many muscle fibers. The *motor unit action potential* (MUAP) is the electric field resulting from the sum of the electric fields emitted by each fiber of the motor unit. In other words, it represents the spatiotemporal summation of individual MAPs originating from muscle fibers that are sufficiently close to a given electrode. This generates a *train* of MUAPs, called *motor unit action potential trains* (MUAPTs). The mixture of MUAPTs coming from different motor units constitute the raw EMG signal (cf. Figure 2.8).

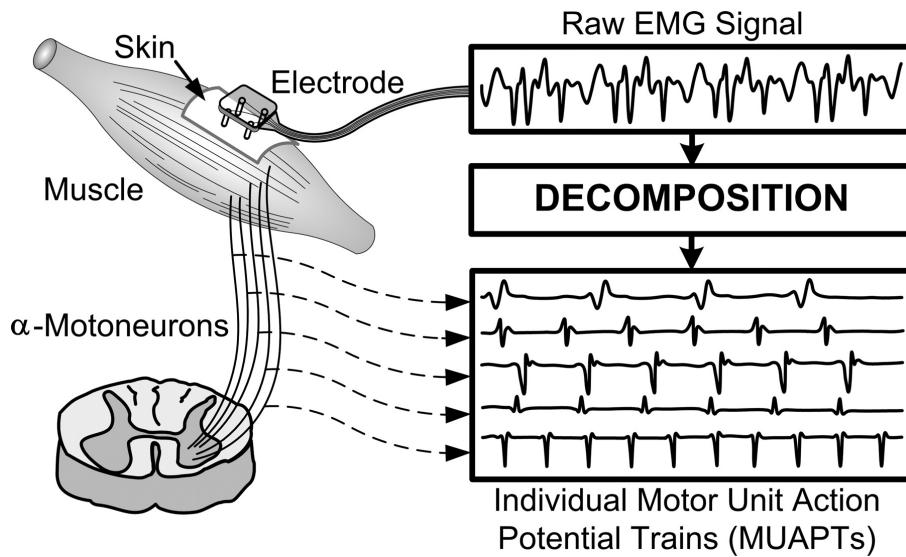


Figure 2.8: Motor unit action potential representation (Figure from De Luca et al., 2006).

To sum up, the EMG signal results from a mixture of recruited motor units: it is composed of the sum of several to many MUAPTs. This signal can vary considerably because of factors such as the muscle length (Babault, Pousson, Michaut, & Van Hoecke, 2003), the distance between the muscle fiber (of interest) and the electrode, the fiber length or the muscle temperature. In the next section, we discuss in more details how this signal can be acquired.

2.2.2 EMG instrumentation and recording

Myoelectric measurements have a long history, starting in the XVII and XVIII centuries with the classical observations that muscle contraction can generate electricity and that electrical impulses can generate muscle contraction. The term of electromyography and the first EMG measures were realised at the end of the XIXth century, and the quality of EMG measurements did not cease to improve since (see Raez, Hussain, & Mohd-Yasin, 2006, for a brief historical perspective).

Two main types of sensors have been used to record EMG signals, varying by their invasiveness. First, *indwelling* (intramuscular) recordings can be acquired via electrodes directly inserted into the muscle. This form of EMG is mostly used in rehabilitation, for diagnosis of muscle function and to examine nerve conduction (Fridlund & Cacioppo, 1986). Second, *surface electromyography* can be recorded at the surface of the skin. Each method is associated with its own type of sensors, its own advantages and disadvantages. Surface electrodes have the advantage of being easy to use and non-invasive. However, their use is limited to (large and) superficial muscles. Moreover, because of the phenomenon of *cross-talk*³, it is difficult to isolate the activity of specific muscles using surface EMG. On the opposite, intramuscular EMG (that can be recorded via a single needle or two wires implanted directly into the muscle) are highly selective and can sometimes record the activity of individual motor units. In addition, indwelling recordings are not submitted to *tissue filtering* (i.e., the fact that muscles tissues act as low-pass filters), in contrast to surface recordings.

³The phenomenon of *cross-talk* can be defined as the mixing of the electrical activity of the muscle of interest with the electrical activity of adjacent or distant muscles, that are not of primary interest.

In reason of the important intercrossing and superposition of facial muscles, surface EMG recorded over facial muscles does not generally represent the activity of a single muscle, but rather a mixture of muscles activations (De Luca, 1997; Rapin, 2011). As a result, it is usually inappropriate, when using surface EMG, to attribute the recorded activity to a single muscle (Fridlund & Cacioppo, 1986). Whereas for the sake of simplicity, we designate sensors by the name of the underlying muscle of interest (e.g., “FRO” for the *frontalis* muscle), it should be kept in mind that these sensors reflect the activity of “sites”, rather than the activity of single muscles.

Aside from *cross-talk*, many other factors can affect the EMG signals. These factors are usually described under three main categories (for more details, see De Luca, 1997):

- The *causative factors*, that have a basic effect on EMG signals. These factors can be further subdivided into two classes: i) the *extrinsic* factors, including factors such as the type of electrode (e.g., size, shape, placement) or the inter-electrode distance and ii) the *intrinsic* factors such as physiological or anatomical factors (e.g., fiber type, fiber diameter, blood flow).
- The *intermediate factors*. These are the physiological phenomena that are influenced by one or more of the causative factors and that in turn influence the deterministic factors, such as the conduction velocity, spatial filtering or the signal *cross-talk*.
- Finally, the *deterministic factors* are influenced by the intermediate factors and have a direct effect on the EMG signal. These include the number of active motor units or the amplitude, duration and shape of the MUAPs.

All these factors contribute to modulating both the amplitude of the EMG signal and its spectral properties (e.g., its mean or median frequency). The importance of these perturbing factors should be acknowledged and controlled as far as possible. In our work, we use state-of-the art surface EMG apparatus, specifically developed to tackle these issues, as well as standardised procedures (more details regarding the EMG apparatus are provided in chapters 3 to 5).

2.2.3 EMG signal processing

The raw EMG signal is a stochastic train of MUAPs. As put by Fridlund & Cacioppo (1986), “when heard through a speaker, the raw EMG signal sounds like popcorn popping”. Therefore, it is usually unsuitable for immediate quantification. In order to illustrate what the EMG signal looks like, we simulated EMG data based on a standard algorithm implemented in the *biosignalEMG* package (Guerrero & Macias-Diaz, 2018). This simulated EMG signal is represented in Figure 2.9.

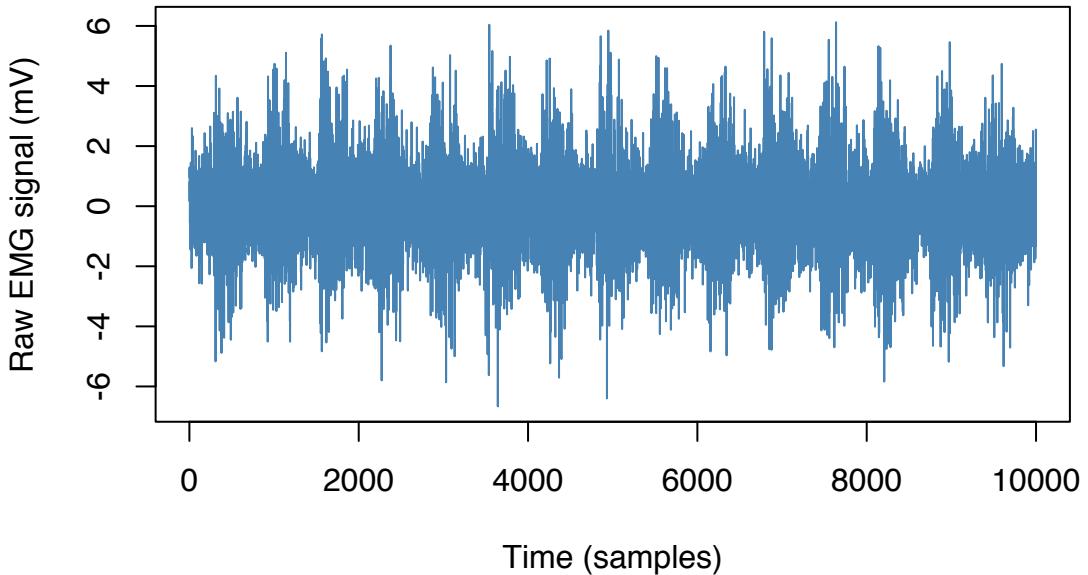


Figure 2.9: Simulated EMG signal.

We usually rectify the EMG signal by taking its absolute value and subtracting the mean in order to correct for any offset (bias) present in the raw data. The result of this operation is represented in Figure 2.10.

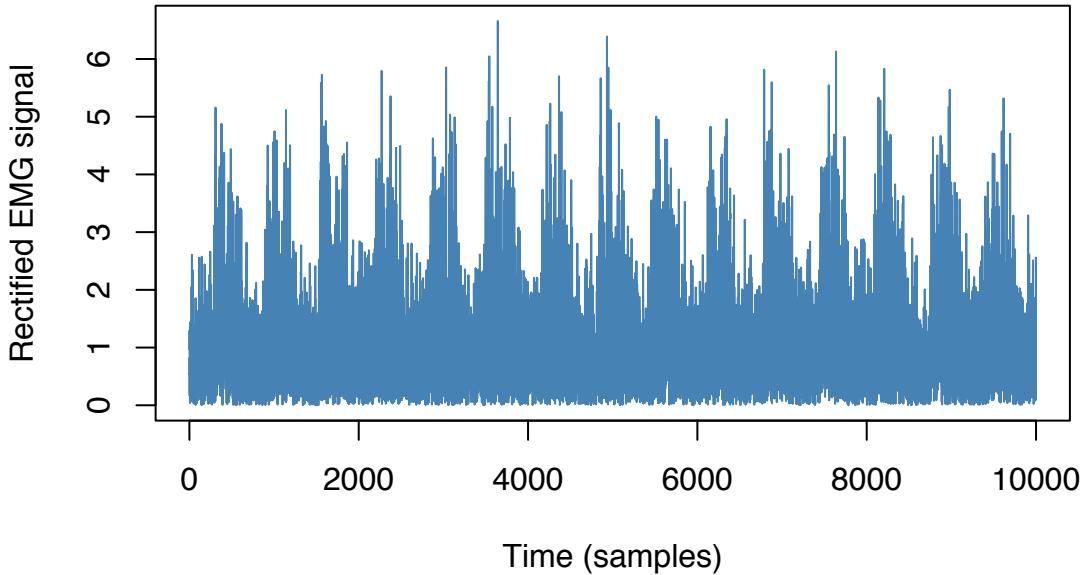


Figure 2.10: Rectified EMG signal.

Then, the signal is usually low-pass filtered, with a cut-off frequency depending on the nature of the study. From there, two main measures can be used to represent the magnitude of the muscle activity⁴. The first one is the *mean absolute value* (MAV), which is computed over a specific interval and where $|x_n|$ is the absolute value of a datum of EMG in the data window.

⁴But see for instance Phinyomark, Nuidod, Phukpattaranont, & Limsakul (2012), for a brief overview of other features that can be extracted from the surface EMG signal.

$$MAV = \frac{1}{N} \sum_{n=1}^N |x_n|$$

The unit of measurement is usually the mV and the MAV calculation is generally similar to the numerical formula for integration (Kamen & Gabriel, 2010). The second one is the *root-mean-square* (RMS) amplitude:

$$RMS = \sqrt{\frac{1}{N} \sum_{n=1}^N x_n^2}$$

where x_n^2 is the squared value of each EMG datum and has both physical and physiological meanings. Put broadly, the RMS is taken to reflect the level of the physiological activities in the motor unit during contraction. Both the MAV and the RMS are illustrated in Figure 2.11.

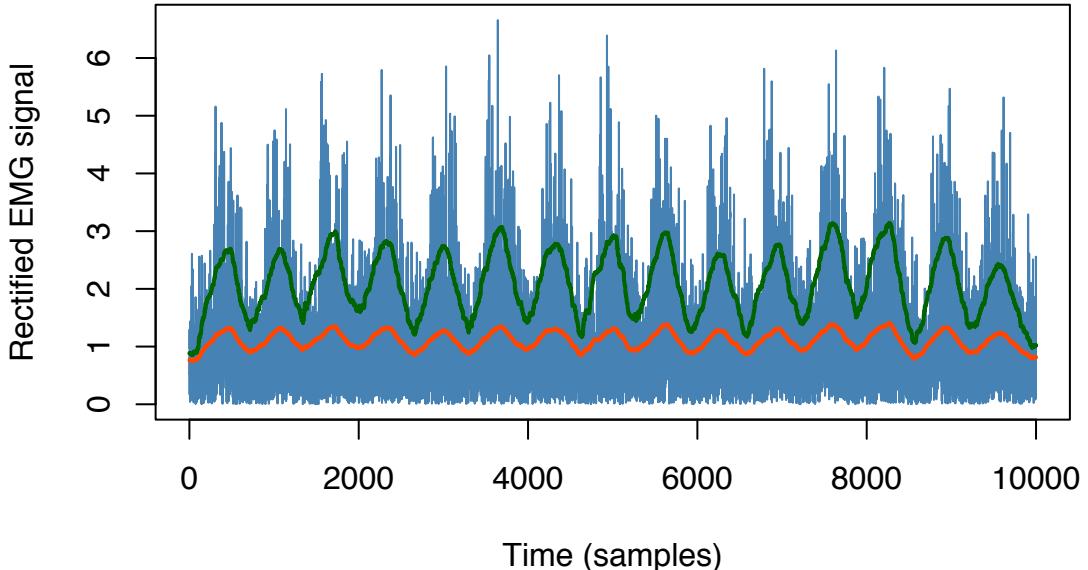


Figure 2.11: Illustration of the MAV (in orange) and RMS (in green) values. These two features are usually highly correlated but differ in magnitude. More precisely, the RMS is proportional to the MAV when the signal has a Gaussian shape.

These features provide the *envelope* of the EMG signal and therefore provide insights about the *amplitude* of the EMG signal. This envelope can then be summarised (e.g., via its mean or median) over a period of interest (e.g., during the utterance of some phoneme).

2.3 Statistical modelling and statistical inference

2.3.1 Limitations of the standard statistical approach in Psychology

Numerous authors have highlighted the limitations inherent to the Null-Hypothesis Significance Testing (NHST) approach and the (exclusive) reliance on p -values and significance testing (e.g., Bakan, 1966; Gigerenzer, 2004; Kline, 2004; Lambdin, 2012; Meehl, 1967; Trafimow et al., 2018). Considering these limitations, some authors have recommended to push away significance testing and to develop the use of effect size

estimates and confidence intervals in order to favour accumulation of evidence and a meta-analytical mode of thinking (e.g., Cumming, 2012, 2014).

However, the apparent superiority of confidence intervals over p -values is an illusion. Indeed, as noted by many observers, confidence intervals are simply inverted significance tests. In other words, the confidence interval represents the range of values that are significant at some α level. Therefore, compared to a p -value, a confidence interval does not bring *any* new inferential value. Moreover, its interpretation might be as hard as the interpretation of p -values. For instance, contrary to a widely shared belief, confidence intervals do not contain the $(1 - \alpha) \cdot 100\%$ most probable values of the parameter (e.g., Morey, Hoekstra, Rouder, Lee, & Wagenmakers, 2015; Nalborczyk et al., 2019b).

That being said, it is fair to acknowledge that using confidence intervals (instead of or in addition to single p -values) do shift the emphasis from a mechanical (mindless) point-hypothesis testing procedure to a more careful consideration of the range of values that are *compatible* with some hypothesis. More importantly, it emphasises the uncertainty that accompanies every statistical procedure. Indeed, we think that most of the caveats that are attributed to a specific statistical procedure (e.g., to NHST) are really caveats of the way it is used. Namely, the fact that is used in a categorical and absolute way. This tendency has been coined as *dichotomania* (i.e., the tendency to consider that results are either present –if significant– or absent –if non-significant), or *trichotomania* (e.g., when considering evidence ratios thresholds).

These biases have been highlighted by many statisticians in the past (e.g., Wasserstein & Lazar, 2016). Very recently, *The American Statistician* published a special issue on *Moving to a World Beyond “ $p < .05$ ”*, with the intention to provide new recommendations for users of statistics (e.g., researchers, policy makers, journalists). This issue comprises 43 original papers aiming to provide new guidelines and practical alternatives to the mindless use of statistics. In the accompanying editorial, Wasserstein, Schirm, & Lazar (2019) summarise these recommendations in the form of the ATOM guidelines: “Accept uncertainty. Be thoughtful, **open**, and **modest**.” We describe below how our statistical approach might be understood in the light of these core principles.

- **Accept uncertainty:** we try to represent and to acknowledge uncertainty in our analyses and conclusions. For instance, we do not conclude and/or infer that an effect is either “present” or “absent”, but we report the *estimated* magnitude of the effect and the uncertainty that comes with this estimation. Additionally, when relevant, we report probabilistic statements based on the posterior distribution.
- **Be thoughtful:** for each analysis opportunity (i.e., for each dataset to analyse), we consider what would be the most appropriate modelling strategy but we also acknowledge that there is no unique best way to analyse a given dataset. In most empirical chapters, we clearly distinguish between confirmatory (preregistered) and exploratory (non-preregistered) statistical analyses. We routinely evaluate the *validity* of the statistical model (and of its assumptions) and we are suspicious of statistical *defaults*. We try to consider the *practical* significance of the results, rather than their *statistical* significance. We use a variety of statistics (e.g., effect sizes, interval estimates, information criteria) to obtain a more diverse picture of the meaning of the results.
- **Be open:** the soundness of a statistical procedure (and more generally, of an inferential procedure) can only be evaluated if it is made transparent to peers and readers for

critical examination. Therefore, we take some space in the next section (but also in each experimental chapter) to motivate our statistical modelling decisions. We also make all R scripts available to ensure the reproducibility of the analyses. We try to be exhaustive in the way we report our analyses and we beware of shortcuts than could hinder important information to the reader.

- **Be modest:** we recognise that there is no unique “true statistical model” and we discuss the limitations of our analyses and conclusions. We also recognise that scientific inference is much broader than statistical inference (e.g., a degenerative research program is much more informative than a non-significant p -value). We try not to conclude anything from a single study without the warranted uncertainty.

To sum up, we try to acknowledge the uncertainty that accompanies every (statistical) inference. In the next section, we present in more details what our approach does entail and we introduce some key technical concepts.

2.3.2 Our statistical approach

In brief, we tried to move from the point-hypothesis mechanical testing to an approach that emphasises parameter estimation, model comparison, and continuous model expansion (e.g., Cumming, 2012, 2014; Gelman et al., 2013; Gelman & Hill, 2006; Judd, McClelland, & Ryan, 2009; Kruschke, 2015; Kruschke & Liddell, 2018a, 2018b; McElreath, 2016). In other words, our approach can be defined as a *statistical modelling* approach rather than a *statistical testing* approach. It means that we try to *model* the data (or rather the process that generated the data), rather than to “test” it. We carefully consider what could be the process that generated the data and we try to model it appropriately. For instance, we do not fit reaction time data, Likert data, or electromyographic data using the same model, as this practice would lead to high rates of erroneous inferences.

Throughout this work, we use Bayesian statistical modelling, not by dogmatism, but because we think the Bayesian approach provides richer inferences than the frequentist one. The main advantage of the Bayesian approach is the explicit use of probability to model the uncertainty (see Box 2.1). By doing so, the Bayesian approach permits to evaluate the probability of a parameter (or a vector of parameters) θ , given a set of data y :

$$p(\theta|y) = \frac{p(y|\theta)p(\theta)}{p(y)}$$

Using this equation (known as Bayes’ theorem), a probability distribution $p(\theta|y)$ can be derived (called the *posterior distribution*), that reflects knowledge about the parameter, given the data and the prior information. This distribution is the goal of any Bayesian analysis and contains all the information needed for inference.

The term $p(\theta)$ corresponds to the *prior distribution*, which specifies the prior information about the parameters (i.e., what is known about θ before observing the data) as a probability distribution. The left hand of the numerator $p(y|\theta)$ represents the *likelihood*, also called the *sampling distribution* or *generative model*, and is the function through which the data affect the posterior distribution. The likelihood function indicates how likely the data are to appear, for each possible value of θ . Finally, $p(y)$ is called the *marginal likelihood*. It is meant to normalise the posterior distribution, that is, to scale it in the “probability world”. It gives the “probability of the data”, summing over

all values of θ and is described by $p(y) = \sum_{\theta} p(\theta)p(y|\theta)$ for discrete parameters, and by $p(y) = \int p(\theta)p(y|\theta)d\theta$ in the case of continuous parameters.

All this pieced together shows that the result of a Bayesian analysis, namely the posterior distribution $p(\theta|y)$, is given by the product of the information contained in the data (i.e., the likelihood) and the information available before observing the data (i.e., the prior). This constitutes the crucial principle of Bayesian inference, which can be seen as an updating mechanism. To sum up, Bayes' theorem allows a prior state of knowledge to be updated to a posterior state of knowledge, which represents a compromise between the prior knowledge and the empirical evidence.

Box 2.1: Probability theory as extended logic

Probability theory has been argued to be nothing more than *extended logic*. In other words, it generalises the rules of logic that apply to discrete events (e.g., TRUE or FALSE events) to continuous events. By doing this move, probability theory gives a way to represent and to quantify the *uncertainty*. Importantly, the rules of probability have the same status as the rules of logic: these rules can be used to derive statements (conclusions) that are guaranteed to be correct given that some premises are correct.

Bayesian statistics can simply be presented as an application of probability theory to statistical analysis. Whereas the dependence of the inferential conclusions on prior assumptions is sometimes presented as a downside of this type of analysis, it is precisely what makes them *optimal* or *coherent* (in the sense of respecting the rules of probability). As put by Vandekerckhove (2018), the claim that Bayesian methods would be invalidated by their reliance on prior assumptions would be akin to conclude that logical deductions are somehow invalidated because they depend on premises.

We also use *multilevel models* (also known as *mixed-models*) to handle complex dependency structures and to obtain more precise estimates. A more accurate description of Bayesian multilevel models is outside the scope of this introductory section but the interested reader is redirected toward several existing tutorial papers (e.g., Nalborczyk et al., 2019a; Nicenboim & Vasishth, 2016; Sorensen, Hohenstein, & Vasishth, 2016). Throughout this work, we also make use of several tools with very distinct properties and uses. For instance, we use Bayes factors (BFs) to quantify the relative evidence for a statistical hypothesis (see Box 2.2), we use information criteria to assess the predictive abilities of our models (see Box 2.3), we use posterior predictive checks as well as a diagnostics tools (e.g., convergence indexes, trace plots) to assess the validity of our models, and we use summary statistics when appropriate to convey the meaning of the main results.

Box 2.2: What is a Bayes factor ?

It is a rule in statistics that every statistic has already been suggested as the *new statistics*. Confidence intervals have been suggested as a replacement to *p*-values, being purportedly more informative and less difficult to interpret. Credible intervals have been suggested as a replacement to confidence intervals, for roughly the same reasons. Bayesian hypothesis testing through Bayes factors (BFs) has also been suggested as a replacement for frequentist hypothesis testing. It has been argued that they permit a richer inference and that they come with a more straightforward interpretation. Whereas this might be true, they nonetheless come with their lot of misinterpretations.

To highlight what BFs are and what they are not, it might be useful to write down the formula used to compute them. To this end, it is useful to write the Bayes rule in its *odds form*, making the BF explicitly visible:

$$\frac{p(H_0|D)}{p(H_1|D)} = \underbrace{\frac{p(D|H_0)}{p(D|H_1)}}_{\text{Bayes factor}} \times \underbrace{\frac{p(H_0)}{p(H_1)}}_{\text{prior odds}}$$

This equation reveals that the *posterior odds*, the ratio of the posterior probability (i.e., how much more probable is hypothesis 1 (H_1) as compared to hypothesis 2 (H_2), after seeing the data D), is equal to the ratio of the probability of the data given the first hypothesis and the probability of the data given the second hypothesis, multiplied by the *prior odds* (i.e., how much more probable was hypothesis 1 (H_1) as compared to hypothesis 2 (H_2), before seeing the data D).

Importantly, what we consider as *evidence* in the Bayesian framework is also known as a *marginal likelihood* and represents the information contained in the data, weighted by the prior information. It is a sum when parameters are discrete or an integral when parameters are continuous.

$$\text{evidence} = p(D|H) = \int p(\theta|H)p(D|\theta, H)d\theta$$

Therefore, the BF does not indicate how much "probable" a hypothesis is, or how much more probable a hypothesis is, compared to another one (this would be to conflate the BF with the posterior odds). Instead, the BF can be (should be) interpreted either i) as a ratio of two *marginal likelihoods* (i.e., a ratio of *evidence*) or ii) as an updating factor, indicating how we should reallocate credibility from prior knowledge (what we knew before seeing the data) to posterior knowledge (what we know after seeing the data).

Bayes factors are often said to have desirable *asymptotic* (i.e., when the number of observations is very large) properties. Indeed, they are *consistent* for model identification. It means that if a "true" statistical model is in the set of models that are compared, using a BF will usually lead to selecting this "true" model with a probability approaching 1 with increasing sample size. Whereas this seems as an appealing property or not depends on the underlying statistical philosophy. Indeed, one could question whether it is sensible to assume a "true model" (an oxymoron) in real life, especially in the social sciences (e.g.,

Burnham & Anderson, 2002, 2004). As Findley (1985) notes: “[...] consistency can be an undesirable property in the context of selecting a model”. A more realistic question is then not to look for the “true” model, but rather for the *best* model for some practical purpose.

The usefulness of information criteria comes from them being approximations of the *out-of-sample deviance* (see Box 2.3). In the present PhD work, we used generalisations of the AIC (especially the WAIC and LOOIC) that also approximate the *out-of-sample deviance* and as such give an indication of how good/bad a model is to predict future (i.e., non-observed) data.

Box 2.3: Information criteria

Hirotugu Akaike noticed that the negative log-likelihood of a model + 2 times its number of parameters was approximately equal to the **out-of-sample deviance** of a model, which lead to what is nowadays famously known as the *Akaike information criterion* (AIC):

$$\text{AIC} = \underbrace{-2 \log(\mathcal{L}(\hat{\theta}|\text{data}))}_{\text{in-sample deviance}} + 2K \approx \text{out-of-sample deviance}$$

where K is the number of parameters of the model and the *deviance* is a measure of discrepancy between the data and the model. Interestingly, we can make a distinction between two types of deviances.

First, the **in-sample deviance** indicates how bad a model is to explain the current dataset (the dataset used to fit the model). Second, and more importantly, the **out-of-sample deviance** indicates how bad a model is to explain a **future** dataset issued from the same data generation process (the same population).

In brief, in the present work, we used various methods but coherently with a few (nuanced) guiding principles. Namely, we favoured a *model comparison* approach (e.g., Burnham & Anderson, 2002, 2004; Judd et al., 2009), we used several statistics when they provide complementary information (e.g., using both posterior probabilities, information criteria or BFs), we assessed the validity of our models (e.g., via posterior predictive checks), we reported these analyses transparently, and we tried to convey uncertainty in our conclusions.

2.4 Overview of the following chapters

The experiments ran during this PhD will be presented as five empirical chapters that can be grouped under two main axes. In the first couple of experiments, we used surface electromyography and muscle-specific relaxation to investigate the involvement of the speech motor system during induced verbal and non-verbal rumination (Chapter 3 & 4). In Chapter 5, we used surface electromyography and machine learning algorithms to decode the muscle-specific EMG correlates of inner speech production. In the last couple of experiments, we switched strategy from the “correlates strategy” to the “interference strategy”, where the goal was to directly interfere with the activity of the speech motor system. More precisely, we used articulatory suppression to disrupt induced rumination in Chapter 6, and we used articulatory suppression to disrupt either induced rumination

or problem-solving in Chapter 7. Finally, in Chapter 8, we summarise the main findings, discuss their implications and suggest ways forward from both a theoretical and an experimental perspective.

Part II

Experimental chapters

OROFACIAL ELECTROMYOGRAPHIC CORRELATES OF INDUCED VERBAL RUMINATION

A dd a summary of the research and brief introduction to this first empirical chapter here...¹

3.1 Abstract

Rumination is predominantly experienced in the form of repetitive verbal thoughts. Verbal rumination is a particular case of inner speech. According to the *Motor Simulation view*, inner speech is a kind of motor action, recruiting the speech motor system. In this framework, we predicted an increase in speech muscle activity during rumination as compared to rest. We also predicted increased forehead activity, associated with anxiety during rumination. We measured electromyographic activity over the *orbicularis oris superior and inferior, frontalis* and *flexor carpi radialis* muscles. Results showed increased lip and forehead activity after rumination induction compared to an initial relaxed state, together with increased self-reported levels of rumination. Moreover, our data suggest that orofacial relaxation is more effective in reducing rumination than non-orofacial relaxation. Altogether, these results support the hypothesis that verbal rumination involves the speech motor system, and provide a promising psychophysiological index to assess the presence of verbal rumination.

3.2 Introduction

As humans, we spend a considerable amount of time reflecting upon ourselves, thinking about our own feelings, thoughts and behaviors. Self-reflection enables us to create and clarify the meaning of past and present experiences (Boyd & Fales, 1983; Nolen-Hoeksema et

¹This experimental chapter is a published paper reformatted for the need of this thesis. Source: Nalborczyk, L., Perrone-Bertolotti, M., Baeyens, C., Grandchamp, R., Polosan, M., Spinelli, E., ... Lœvenbruck, H. (2017). Orofacial Electromyographic Correlates of Induced Verbal Rumination. *Biological Psychology*, 127, 53-63. <https://dx.doi.org/10.1016/j.biopsych.2017.04.013>.

al., 2008). However, this process can lead to unconstructive consequences when self-referent thoughts become repetitive, abstract, evaluative, and self-critical (Watkins, 2008).

Indeed, rumination is most often defined as a repetitive and recursive mode of responding to negative affect (Ripplere, 1977) or life situations (Robinson & Alloy, 2003). Although rumination is a common process that can be observed in the general population (Watkins, 2008), it has been most extensively studied in depression and anxiety. Depressive rumination has been thoroughly studied by Susan Nolen-Hoeksema, who developed the Response Style Theory (RST, Nolen-Hoeksema, 1991a). According to the RST, depressive rumination is characterized by an evaluative style of processing that involves recurrent thinking about the causes, meanings, and implications of depressive symptoms. Even though rumination can involve several modalities (i.e., visual, sensory), it is a predominantly verbal process (Goldwin & Behar, 2012; McLaughlin, Borkovec, & Sibrava, 2007). In this study, we focus on verbal rumination, which can be conceived of as a particularly significant form of inner speech.

Inner speech or covert speech can be defined as silent verbal production in one's mind or the activity of silently talking to oneself (Zivin, 1979). The nature of inner speech is still a matter of theoretical debate (for a review, see Perrone-Bertolotti et al., 2014). Two opposing views have been proposed in the literature: the *Abstraction view* and the *Motor Simulation view*. The *Abstraction view* describes inner speech as unconcerned with articulatory or auditory simulations and as operating on an amodal level. It has been described as "condensed, abbreviated, disconnected, fragmented, and incomprehensible to others" (Vygotsky, 1987). It has been argued that important words or grammatical affixes may be dropped in inner speech (Vygotsky, 1987) or even that the phonological form or representation of inner words may be incomplete (Dell & Repka, 1992; Sokolov, 1972). MacKay (1992) stated that inner speech is nonarticulatory and nonauditory and that "Even the lowest level units for inner speech are highly abstract" (p.122).

In contrast with this *Abstraction view*, the physicalist or embodied view considers inner speech production as mental simulation of overt speech production. As such, it can be viewed as similar to overt speech production, except that the motor execution process is blocked and no sound is produced (Grzes & Decety, 2001; Postma & Noordanus, 1996). Under this *Motor Simulation view*, a continuum exists between overt and covert speech, in line with the continuum drawn by Decety & Jeannerod (1996) between imagined and actual actions. This hypothesis has led certain authors to claim that inner speech by essence should share features with speech motor actions (Feinberg, 1978; Jones & Fernyhough, 2007). The *Motor Simulation view* is supported by several findings. First, covert and overt speech have comparable physiological correlates: for instance, measurements of speaking rate(Landauer, 1962) and respiratory rate (Conrad & Schönle, 1979) are similar in both. A prediction of the *Motor Simulation view* is that the speech motor system should be recruited during inner speech. Subtle muscle activity has been detected in the speech musculature using electromyography (EMG) during verbal mental imagery, silent reading, silent recitation (Jacobson, 1931; Livesay, Liebke, Samaras, & Stanley, 1996; McGuigan & Dollins, 1989; Sokolov, 1972), and during auditory verbal hallucination in patients with schizophrenia (Rapin et al., 2013b). Second, it has been shown that covert speech production involves a similar cerebral network as that of overt speech production. Covert and overt speech both recruit essential language areas in the left hemisphere (for a review, see Perrone-Bertolotti et al., 2014). However, there are differences. Consistent with the *Motor Simulation view* and the notion of a continuum between covert and overt speech, overt speech is associated with more activity in motor and premotor areas than

inner speech (e.g., Palmer et al., 2001). This can be related to the absence of articulatory movements during inner verbal production. In a reciprocal way, inner speech involves cerebral areas that are not activated during overt speech (Basho, Palmer, Rubio, Wulfeck, & Müller, 2007). Some of these activations (cingulate gyrus and superior rostral frontal cortex) can be attributed to the inhibition of overt responses.

These findings suggest that the processes involved in overt speech include those required for inner speech (except for inhibition). Several studies in patients with aphasia support this view: overt speech loss can either be associated with an impairment in inner speech (e.g., Levine, Calvanio, & Popovics, 1982; Martin & Caramazza, 1982) or with intact inner speech: only the later phases of speech production (execution) being affected by the lesion (Baddeley & Wilson, 1985; Marshall, Rappaport, & Garcia-Bunuel, 1985; Vallar & Cappa, 1987). Geva, Bennett, Warburton, & Patterson (2011) have reported a dissociation that goes against this view, however. In three patients with chronic post-stroke aphasia (out of 27 patients), poorer homophone and rhyme judgement performance was in fact observed in covert mode compared with overt mode. A limitation of this study, though, was that the task was to detect rhymes in written words, which could have been too difficult for the patients. To overcome this limitation, Langland-Hassan, Faries, Richardson, & Dietz (2015) have tested aphasia patients with a similar task, using images rather than written words. They also found that most patients performed better in the overt than in the covert mode. They inferred from these results that inner speech might be more demanding in terms of cognitive and linguistic load, and that inner speech may be a distinct ability, with its own neural substrates. We suggest an alternative interpretation to this dissociation. According to our view, rhyme and homophone judgements rely on auditory representations of the stimuli (e.g., Paulesu, Frith, & Frackowiak, 1993). Overt speech provides a strong acoustic output that is fed back to the auditory cortex and can create an auditory trace, which can be used to monitor speech. In the covert mode, the auditory output is only mentally simulated, and its saliency in the auditory system is lesser than in the overt mode. This is in accordance with the finding that inner speech is associated with reduced sensory cortex activation compared with overt speech (Shuster & Lemieux, 2005). In patients with aphasia, the weakened saliency of covert auditory signals may be accentuated for two reasons: first, because of impairment in the motor-to-auditory transformation that produces the auditory simulation, and second, because of associated auditory deficits. Therefore, according to our view, the reduced performance observed in rhyme and homophone judgement tasks in the covert compared with the overt mode in brain-injured patients, simply indicates a lower saliency of the auditory sensations evoked during inner speech compared with the actual auditory sensations fed back during overt speech production. In summary, these findings suggest that overt and covert speech share common subjective, physiological and neural correlates, supporting the claim that inner speech is a motor simulation of overt speech.

However, the *Motor Simulation view* has been challenged by several experimental results. Examining the properties of errors during the production of tongue twisters, Oppenheim & Dell (2010) showed that speech errors display a lexical bias in both overt and inner speech. According to these researchers, errors also display a phonemic similarity effect (or articulatory bias), a tendency to exchange phonemes with common articulatory features, but this second effect is only observed with overt speech or with inner speech accompanied with mouthing. This has led Oppenheim & Dell (2010) to claim that inner speech is fully specified at the lexical level, but that it is impoverished at lower featural (articulatory) levels. This claim, related to the *Abstraction view*, is still debated however, as a phonemic similarity effect has been found by Corley, Brocklehurst, & Moat (2011). Their

findings suggest that inner speech is in fact specified at the articulatory level, even when there is no intention to articulate words overtly. Other findings however, may still challenge the Motor Simulation view. Netsell, Ashley, & Bakker (2010) have examined covert and overt speech in persons who stutter (PWS) and typical speakers. They have found that PWS were faster in covert than in overt speech while typical speakers presented similar overt and covert speech rates. This can be interpreted in favour of the *Abstraction view*, in which inner representations are not fully specified at the articulatory level, which would explain why they are not disrupted in PWS speech. Altogether, these results suggest that full articulatory specification may not always be necessary for inner speech to be produced.

The aim of this study is to examine the physiological correlates of verbal rumination in an attempt to provide new data in the debate between motor simulation and abstraction. A prediction of the *Motor Simulation view* is that verbal rumination, as a kind of inner speech, should be accompanied with activity in speech-related facial muscles, as well as in negative emotion or anxiety-related facial muscles, but should not involve non-facial muscles (such as arm muscles). Alternatively, the *Abstraction view* predicts that verbal rumination should be associated with an increase in emotion-related facial activity, without activity in speech-related muscles and non-facial muscles.

There is strong interest in the examination of physiological correlates of rumination as traditional assessment of rumination essentially consists of self-reported measures. The measurement of rumination as conceptualized by Nolen-Hoeksema (1991a) was operationalized by the development of the Ruminative Response Scale (RRS), which is a subscale of the response style questionnaire (Nolen-Hoeksema & Morrow, 1991). The RRS consists of 22 items that describe responses to dysphoric mood that are self-focused, symptom-focused, and focused on the causes and consequences of one's mood. Based on this scale, Treynor, Gonzalez, & Nolen-Hoeksema (2003) have offered a detailed description of rumination styles and more recently, Watkins (2008) has further characterized different modes of rumination. The validity of these descriptions is nevertheless based on the hypothesis that individuals have direct and reliable access to their internal states. However, self-reports increase reconstruction biases (e.g., Brewer, 1986; Conway, 1990) and it is well known that participants have a very low level of awareness of the cognitive processes that underlie and modulate complex behaviors (Nisbett & Wilson, 1977).

In order to overcome these difficulties, some authors have attempted to quantify state rumination and trait rumination more objectively, by recording physiological or neuroanatomical correlates of rumination (for a review, see Siegle & Thayer, 2003). Peripheral physiological manifestations (e.g., pupil dilation, blood pressure, cardiac rhythm, cardiac variability) have been examined during induced or chronic rumination. Vickers & Vogeltanz-Holm (2003) have observed an increase in systolic blood pressure after rumination induction, suggesting the involvement of the autonomic nervous system in rumination. Moreover, galvanic skin response has shown to be increased after a rumination induction, in highly anxious women (Sigmon, Dorhofer, Rohan, & Boulard, 2000). According to Siegle & Thayer (2003), disrupted autonomic activity could provide a reliable physiological correlate of rumination. In this line, Key, Campbell, Bacon, & Gerin (2008) have observed a diminution of the high-frequency component of heart rate variability (HF-HRV) after rumination induction in people with a low tendency to ruminate (see also Woody, McGeary, & Gibb, 2014). A consistent link between perseverative cognition and decreased HRV was also found in a meta-analysis conducted by Ottaviani et al. (2015). Based on these positive results and on suggestions that labial EMG activity may accompany inner speech and therefore rumination, our aim was to examine facial EMG as a potential

correlate of rumination and HRV as an index to examine concurrent validity.

In addition to labial muscular activity, we also recorded forehead muscular activity (i.e., *frontalis* muscle) because of its implication in prototypical expression of sadness (e.g., Ekman & Friesen, 1978; Kohler et al., 2004), reactions to unpleasant stimuli (Jäncke et al., 1996), and anxiety or negative emotional state (Conrad & Roth, 2007)². Our hypothesis was that *frontalis* activity could be an accurate electromyographic correlate of induced rumination, as a negatively valenced mental process.

In this study, we were also interested in the effects of relaxation on induced rumination. Using a relaxation procedure targeted on muscles involved in speech production is a further way to test the reciprocity of the link between inner speech (verbal rumination) and orofacial muscle activity. If verbal rumination is a kind of action, then its production should be modulated in return by the effects of relaxation on speech effectors. This idea is supported by the results of (among others) Cefidekhanie, Savariaux, Sato, & Schwartz (2014), who have observed substantial perturbations of inner speech production while participants had to realize forced movements of the articulators.

In summary, the current study aimed at evaluating the *Motor Simulation view* and the *Abstraction view* by using objective and subjective measures of verbal rumination. To test the involvement of the orofacial motor system in verbal rumination, we used two basic approaches. In the first approach, we induced verbal rumination and examined concurrent changes in facial muscle activity (Experiment 1). In the second approach, we examined whether orofacial relaxation would reduce verbal rumination levels (Experiment 2). More specifically, in Experiment 1, we aimed to provide an objective assessment of verbal rumination using quantitative physiological measures. Thus, we used EMG recordings of muscle activity during rumination, focusing on the comparison of speech-related (i.e., two lip muscles *orbicularis oris superior* and *orbicularis oris inferior*) and speech-unrelated (i.e., forehead *frontalis*- and forearm *flexor carpi radialis*) muscles. Under the *Motor Simulation view*, an increase in lip and forehead EMG activity should be observed after rumination induction, with no change in forearm EMG activity, associated with an increase in self-reported rumination. Alternatively, under the *Abstraction view*, an increase in forehead activity should be observed, associated with an increase in self-reported rumination, and no changes in either lip or forearm activity should be noted.

In Experiment 2, in order to assess the reciprocity of the rumination and orofacial motor activity relationship, we evaluated the effects of orofacial relaxation on rumination. More specifically, we compared three kinds of relaxation: i) Orofacial Relaxation (i.e., lip muscles), ii) Arm Relaxation (i.e., to differentiate effects specific to speech-related muscle relaxation) and iii) Story Relaxation (i.e., to differentiate effects specific to attentional distraction). If the *Motor simulation view* is correct, we predicted a larger decrease of lip and forehead muscle activity after an Orofacial Relaxation than after an Arm Relaxation (associated with a larger decrease in self-reported rumination), which should also be larger than after listening to a story. We also predicted that forearm activity should remain stable across the

²The *corrugator supercilii* was another potential site, as it is sensitive to negative emotions. However, it has been claimed to be mostly activated for strong emotions such as fear/terror, anger/rage and sadness/grief (Ekman & Friesen, 1978; Sumitsuji, Matsumoto, Tanaka, Kashiwagi, & Kaneko, 1967). The rumination induction used in this study was designed to have participants self-reflect and brood over their failure at the I.Q. test. It was not meant to induce such strong emotions. Several studies have reported increased activity in the *frontalis* muscle at rest in anxious or generalized anxiety disorder patients (for a review, see Conrad & Roth, 2007). We expected the type of emotional state induced by rumination to be closer to anxiety or worry than to strong emotions like fear, anger or grief. It was therefore more appropriate to record non-speech facial activity in the *frontalis* rather than in the *corrugator*.

three conditions (i.e., should not decrease after relaxation). Alternatively, if the *Abstraction view* is correct, we predicted that none of the relaxation conditions should have an effect on lip or arm activity, because none of these should have increased after induction. However, we expected to observe a decrease in forehead activity and self-reported rumination after Orofacial or Arm relaxation, this decrease being larger than after listening to a Story. Importantly, we predicted that, under the *Abstraction View* no superiority of the Orofacial relaxation should be observed over the Arm relaxation.

3.3 Methods

3.3.1 Participants

Because of the higher prevalence of rumination in women than in men (see Johnson & Whisman, 2013, for a recent meta-analysis), we chose to include female participants only. Seventy-two female undergraduate students from Univ. Grenoble Alpes, native French speaking, participated in our study. One participant presenting aberrant data (probably due to inadequate sensor sticking) was removed from analyses. Final sample consisted of seventy-one undergraduate female students ($M_{age} = 20.58$, $SD_{age} = 4.99$). They were recruited by e-mail diffusion lists and participated in the experiment for course credits. They did not know the goals of the study. The cover story presented the research as aiming at validating a new I.Q. test, more sensitive to personality profiles. Participants reported having no neurologic or psychiatric medical history, no language disorder, no hearing deficit, and taking no medication. Each participant gave written consent and this study has been approved by the local ethical committee (CERNI, Nř 2015-03-03-61).

3.3.2 Material

EMG signals were detected with Trigno™ Mini sensors (Delsys Inc.) at a sampling rate of 1926 samples/s with a band pass of 20 Hz (12 dB/oct) to 450 Hz (24 dB/oct) and were amplified by a Trigno™ 16-channel wireless EMG system (Delsys Inc.). The sensors consisted of two 5 mm long, 1 mm wide parallel bars, spaced by 10 mm, which were attached to the skin using double-sided adhesive interfaces. The skin was cleaned by gently scrubbing it with 70% isopropynol alcohol. EMG signals were then synchronized using the PowerLab 16/35 (ADInstrument, PL3516). Raw data from the EMG sensors were then resampled at a rate of 1 kHz and stored in digital format using Labchart 8 software (ADInstrument, MLU60/8). As shown in Figure 3.1, bipolar surface EMG recordings were obtained from two speech-related labial muscles: *orbicularis oris superior* (OOS) and *orbicularis oris inferior* (OOI), as well as from one non speech-related but negative-affect-related facial muscle: *frontalis* (FRO) and from one non-facial and non speech-related muscle: *flexor carpi radialis* (FCR) on the non-dominant forearm. The latter pair of electrodes was used to check whether the rumination induction would cause any muscle contraction, outside of the facial muscles. The same sensor layout was used for all participants. Asymmetrical movements of the face have been shown in speech and emotional expression. As reviewed in Everdell, Marsh, Yurick, Munhall, & Paré (2007), the dominant side of the face displays larger movements than the left during speech production, whereas the non-dominant side is more emotionally expressive. To optimise the capture of speech-related activity, the OOS and OOI sensors were therefore positioned on the dominant side of the body (i.e. the right side for right-handed participants). To optimise the capture of emotion-related activity,

the FRO sensor was positioned on the non-dominant side. To minimise the presence of involuntary manual gestures during the recording, the FCR sensor was positioned on the non-dominant side. Each pair of electrodes was placed parallel with the direction of the muscle fibers, at a position distant from the innervation zones and the muscle tendon interface, following the recommendations of De Luca (1997). The experiment was video-monitored using a Sony HDR-CX240E video camera to track any visible facial movements. A microphone was placed 20–30 cm away from the participant's lips to record any faint vocal production during rumination. Stimuli were displayed with E-prime 2.0 (<http://www.pstnet.com>) on a 19-inch color monitor.

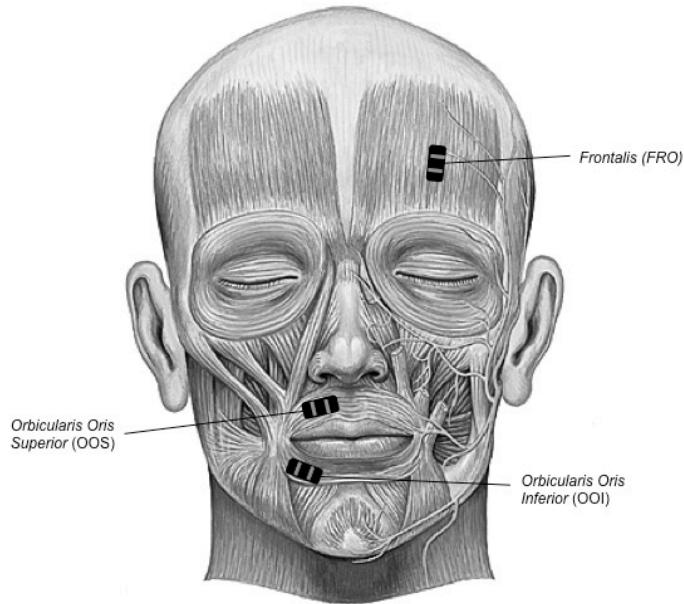


Figure 3.1: Facial muscles of interest. Two speech-related labial muscles: *orbicularis oris superior* (OOS) and *orbicularis oris inferior* (OOI); as well as one non speech-related but sadness-related facial muscle: *frontalis* (FRO).

3.3.3 Procedure

This study consisted of two parts. The first part was carried out a week before the EMG experiment and consisted in checking the inclusion criteria. We checked that participants did not exceed a threshold on a depressive symptoms scale. This was assessed using the French version of the *Center for Epidemiologic Studies Depression* scale (CES-D, Fuhrer & Rouillon, 1989), which evaluates the level of depressive symptom in subclinical population. We also collected information about any potential speech, neurologic, neuromuscular or cardiac disorders and about academic curriculum. Finally, the tendency to ruminate (i.e., trait rumination) in daily life was evaluated using the French version of the *Mini-CERTS* (Cambridge-Exeter Repetitive Thought Scale, Douilliez, Philippot, Heeren, Watkins, & Barnard, 2012). The second part included two EMG interdependent experiments related to *Rumination Induction* and *Rumination Reduction by Muscle Relaxation*. Specifically, Experiment 1 consisted of acquiring physiological EMG data during rest and induced rumination and Experiment 2 consisted of acquiring physiological EMG data after different kinds of relaxation (see below).

During both Experiment 1 and Experiment 2, momentary rumination was assessed using four different Visual Analogue Scales (VAS, the first two being adapted and translated to French from Huffziger, Ebner-Priemer, Koudela, Reinhard, & Kuehner, 2012) rated from 0 to 100: i) “At this moment, I am thinking about my feelings” (referred to as VAS “*Feelings*”), ii) “At this moment, I am thinking about my problems” (referred to as VAS “*Problems*”), iii) “At this moment, I am brooding about negative things” (referred to as VAS “*Brooding*”) and iv) “At this moment, I am focused on myself” (referred to as VAS “*Focused*”).

3.3.3.1 Experiment 1: rumination induction

Participants were seated in front of a computer screen in a comfortable and quiet room. EMG sensors were positioned as explained above (see Figure 3.1). Before the rumination induction, each participant underwent a non-specific relaxation session (i.e., without targeting specific muscles) in order to minimize inter-individual initial thymic variability (approximate duration 330 s). Immediately after, participants were instructed to remain silent and not to move for one minute to carry out EMG “baseline” measurements. Then, participants’ initial level of rumination was assessed using the four VASs.

Subsequently, participants were invited to perform a 15-min I.Q. test, which was presented on the computer screen facing them. They were instructed to correctly respond to three types of I.Q. questions (logical, mathematical and spatial-reasoning questions) in a very short time (30 s). Most of the questions were very difficult, if not impossible, to correctly answer in 30 s. We included ten different questions for each of the three types of I.Q. question: ten logical questions (e.g., finding the next number of a Fibonacci sequence), ten mathematical questions (e.g., “What is the result of the following calculus: (30/165) (70/ 66)”) and ten spatial-reasoning questions (e.g., finding the next figure of a series). Forced-failure tasks have extensively been employed in the literature to induce a slightly negative mood, ideal for subsequent rumination induction (e.g., Lemoult & Joormann, 2014; Randenborgh, Hüffmeier, LeMoult, & Joormann, 2010).

After the I.Q. test, participants were invited to reflect upon the causes and consequences of their feelings, during five minutes (rumination induction). This method is based on the induction paradigm developed by Nolen-Hoeksema & Morrow (1993). The classical paradigm uses a series of prompts. In order to avoid the potential confound in muscle activity induced by silent reading, we did not use the full paradigm. We simply summarised the series of prompts by one typical induction sentence. During this period, participants were asked to remain silent and not to move, while EMG recordings were carried out (i.e., EMG Post-induction measures). EMG signals of rumination were collected during the last minute of this period. Finally, participants were instructed to self-report momentary rumination on the four VASs.

3.3.3.2 Experiment 2: rumination reduction by relaxation

After Experiment 1, participants were randomly allocated to one of three groups. In the first group, participants listened to a pre-recorded relaxation session that was focused on orofacial speech-related muscles (“*Orofacial Relaxation*” condition). In the second group, relaxation was focused on the arm muscles (“*Arm Relaxation*” condition). In the third group, participants simply listened to a story, read by the same person, for an equivalent duration (“*Story*” condition, detailed content of the story can be found in the supplementary materials, in French). In summary, the first condition allowed us to evaluate the effects of targeted speech muscle relaxation on rumination. The second condition

allowed evaluating the effects of a non-orofacial relaxation (i.e., speech-unrelated muscles) while the third condition allowed controlling for effects of attentional distraction during relaxation listening.

The speeches associated with the three conditions, relaxation sessions and story listening session, were delivered to the participants through loudspeakers. They were recorded by a professional sophrology therapist in an anechoic room at GIPSA-lab (Grenoble, France) and were approximately of the same duration (around 330 s).

After the relaxation/distraction session, participants were asked to remain silent and not to move during one minute, during which EMG measurements were collected (EMG Post-relaxation measures). Finally, participants were instructed to self-report rumination on the four VASs.

3.3.4 Data processing and analysis

3.3.4.1 EMG data processing

EMG signal pre-processing was carried out using Labchart 8. The EMG data were high-pass filtered using a Finite Impulse Response (FIR) filter at a cut-off of 20 Hz, using the Kaiser window method with $\beta = 6$. Then, output of this first filter was to a low-pass filtered at a cut-off of 450 Hz (with the same parameters), in order to focus on the 20–450 Hz frequency band, following current recommendations for facial EMG studies (Boxtel, 2001; De Luca, 1997; De Luca, Donald Gilmore, Kuznetsov, & Roy, 2010).

Although we specifically asked participants to remain silent and not to move during EMG data collection, tiny facial movements (such as biting one's lips) or vocal productions sometimes occurred. Periods with such facial movement or vocal production were excluded from the analysis. To do this, visual inspection of audio, video, and EMG signal was performed. Specifically, for the EMG signals, we compared two methods of signal selection. The first one consisted of setting a threshold on the absolute value of the EMG signal and portions of signals above this threshold were removed. This threshold was empirically chosen using visual inspection of a few samples and set to the mean EMG value plus 6 SDs. The second method consisted of manually removing periods of time that included visually obvious bursts of EMG activity, corresponding to overt contraction (as in Rapin et al., 2013a). Based on samples from a few participants, the comparisons between these two methods showed that the automatic threshold method was somewhat less sensitive to overt movements. Therefore, the second method was used, as it was more conservative and less prone to leave data related to irrelevant overt movements.

After pre-processing, EMG data were exported from Labchart software to Matlab r2014a (Version 8.3.0.532, www.mathworks.fr). For each EMG signal, mean values were computed under Matlab, using 200 ms sliding windows. The average of these mean values were calculated for each recording session (baseline, after induction and after relaxation/induction). This provided a score for each muscle of interest (OOS, OOI, FCR, FRO) in each Session (Baseline, Post-Induction, Post-Relaxation) for each participant³.

³Because of constraints attributable to the design of our experiment, we were not able to perform conventional control measures (e.g., time of the day, food consumption, sport activity, smoking habits, etc.). Moreover, in our study, periods of signal recording had to be shorter than usual HRV analysis time periods (cf. methodology section). Although recent studies suggest that “ultrashort term” HRV analysis seems to correlate quite well with HRV analysis performed on longer periods of time (Brisinda et al., 2013; Salahuddin, Cho, Jeong, & Kim, 2007), we cannot exclude that our measurements might be unreliable. For these reasons, we chose not to present HRV results in this report and to focus on EMG results as well as subjective reports of

3.3.4.2 Statistical analyses

Absolute EMG values are not meaningful as muscle activation is never null, even in resting conditions, due in part to physiological noise (Tassinary, Cacioppo, & Vanman, 2007). In addition, there are inter-individual variations in the amount of EMG activity in the baseline. To normalise for baseline activity across participants, we used a differential measure and expressed EMG amplitude as a percentage of baseline level (Experiment 1) or of post-induction level (Experiment 2).

To model EMG amplitude variations in response to the rumination induction (Experiment 1) and relaxation (Experiment 2), we used a bayesian multivariate regression model with the natural logarithm of the EMG amplitude (expressed in % of baseline level) as an outcome, in an intercept-only model (in Experiment 1), and using Condition (Orofacial, Arm or Story) as a categorical predictor in Experiment 2. We used the same strategy (two multivariate models) to analyse VAS scores (expressed in relative changes) along the two experiments.

These analyses were conducted using RStudio (RStudio Team, 2018) and 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 (e.g., Hamiltonian Monte-Carlo), which allow yielding posterior distributions that are straightforward to use for interval estimation around all parameters. Two MCMC simulations (or “chains”) were run for each model, including 100,000 iterations, a warmup of 10,000 iterations, and a thinning interval of 10. Posterior convergence was assessed examining autocorrelation and trace plots, as well as the Gelman-Rubin statistic. Fixed effects were estimated via the posterior mean and 95% highest density intervals (HDIs), where an HDI interval is the Bayesian analogue of a classical confidence interval⁴.

This strategy allowed us to examine posterior probability distribution on each parameter of interest (i.e., effects of session and condition on each response variable). When applicable, we also report evidence ratios (ERs), computed using the hypothesis function of the `brms` package (Bürkner, 2018). These evidence ratios are simply the posterior probability under a hypothesis against its alternative (Bürkner, 2018). We also report summary statistics (mean and HDI) of Cohen’s d effect sizes, computed from the posterior samples.

3.4 Results

3.4.1 Experiment 1: rumination induction

The evolution of VAS scores (for the four assessed scales: Feelings, Problems, Brooding, and Focused) and EMG (for the four muscles: OOS, OOI, FCR and FRO) activity from baseline to post-induction were examined.

3.4.1.1 Self-reported rumination measures: VAS scores

Results for VAS relative changes based on the multivariate models described earlier are shown in the right panel of Figure 3.2. Thereafter, α represents the mean of the posterior rumination.

⁴While not suffering from the misunderstandings associated with frequentist confidence intervals (for more details, see for instance Morey et al., 2015).

distribution of the intercept. Raw pre- and post-induction scores are provided in the supplementary materials.

Mean VAS score on the Feelings scale was slightly lower after induction ($\alpha = 5.55$, 95% HDI [-10.89, 0.24], $d = 0.23$, 95% HDI [-0.46, 0.01]), while Problems score was slightly higher ($\alpha = 3.99$, 95% HDI [-2.04, 9.83], $d = 0.15$, 95% HDI [-0.08, 0.37]). We observed a strong increase of the score on the Brooding scale ($\alpha = 14.45$, 95% HDI [8.07, 20.72], $d = 0.50$, 95% HDI [0.26, 0.74]), and a strong decrease on the Focused scale ($\alpha = 11.63$, 95% HDI [-17, 6.07], $d = 0.48$, 95% HDI [-0.72, 0.24]). As we examined the fit of the intercept-only model, these estimates represent the posterior mean for each muscle.

In the following, we report the mean (indicated by the Greek symbol ρ) and the 95% HDI of the posterior distribution on the correlation coefficient (ρ). Examination of the correlation matrix estimated by the multivariate model revealed no apparent correlation neither between Feelings and Problems scales ($\rho = 0.01$, 95% HDI [-0.23, 0.22]), nor between Feelings and Brooding ($\rho = 0.08$, 95% HDI [-0.15, 0.30]). However, we observed a strong positive correlation between Problems and Brooding VASs ($\rho = 0.64$, 95% HDI [.49, 0.76]), a positive correlation between Feelings and Focused ($\rho = 0.30$, 95% HDI [.08, 0.50]), and a negative correlation between Problems and Focused ($\rho = 0.30$, 95% HDI [-0.49, 0.08]), as well as between Brooding and Focused ($\rho = 0.18$, 95% HDI [-0.39, 0.05]).

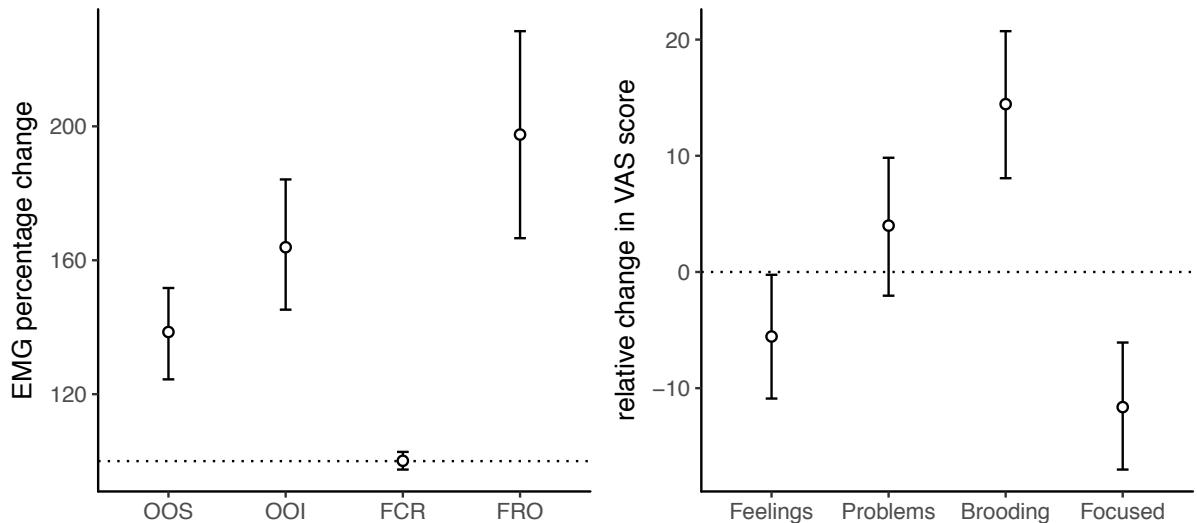


Figure 3.2: Posterior mean (white dots) and 95% credible intervals for the EMG amplitude (expressed in percentage of baseline level, left panel), and the VAS score (expressed in relative change from baseline, right panel). N = 71 (for each muscle and each VAS). Dashed line represents the null value (i.e., 100% for the EMG amplitude and 0 for the VAS scores).

3.4.1.2 EMG

Results for EMG data based on the multivariate model described earlier are shown in the left panel of Figure 3.2. Summary statistics were computed on posterior samples transformed back from log scale.

Mean EMG amplitude for OOS was higher after induction ($\alpha = 138.57$, 95% HDI [124.43, 151.71], $d = 0.66$, 95% HDI [0.49, 0.84]) as well as for OOI ($\alpha = 163.89$, 95% HDI [145.24, 184.14], $d = 0.77$, 95% HDI [0.61, 0.94]), and FRO ($\alpha = 197.55$, 95% HDI [166.59, 228.42], d

= 0.74, 95% HDI [0.59, 0.89]). Effects on the FCR were approximately null ($\alpha = 100.10$, 95% HDI [97.48, 102.76], $d = 0.01$, 95% HDI [-0.24, 0.23]).

Examination of the correlation matrix estimated by the bayesian multivariate model revealed a positive correlation between OOS and OOI EMG amplitudes ($\rho = 0.44$, 95% HDI [.24, 0.61]), while no apparent correlations neither between OOS and FCR ($\rho = 0.09$, 95% HDI [-0.14, 0.31]), OOS and FRO ($\rho = 0.12$, 95% HDI [-0.11, 0.35]), OOI and FCR ($\rho = 0.02$, 95% HDI [-0.21, 0.25]), FRO and FCR ($\rho = 0.06$, 95% HDI [-0.28, 0.17]), nor OOI and FRO ($\rho = 0.07$, 95% HDI [-0.16, 0.29]). Scatterplots, marginal posterior distributions and posterior distributions on correlation coefficients are available in supplementary materials.

In order to check whether the propensity to ruminate could predict the effects of the rumination induction on EMG amplitude, we compared the multivariate model described above, with a similar model but with the score on the abstract dimension of the Mini-CERTS as an additional predictor. We compared these models using the widely applicable information criterion (WAIC; Watanabe, 2010), via the WAIC function of the brms package (Bürkner, 2018). Results showed that the intercept-only model had a lower WAIC (WAIC = 177.39) than the more complex model (WAIC = 182.01), indicating that there is no predictive benefit in adding the Mini-CERTS score as a predictor.

3.4.1.3 Correlations between EMG amplitudes and VAS scores

Correlations between EMG amplitudes and VAS scores were examined using the BayesianFirstAid package (Bååth, 2018), using 15,000 iterations for each correlation coefficient. Both estimated correlation coefficients (ρ s) and 95% HDIs are reported in Table XX.

3.4.2 Experiment 2: rumination reduction by relaxation

In the second experiment, we aimed at comparing the evolution in EMG activity and VAS scores from post-induction to post-relaxation in three different conditions: Orofacial relaxation, Arm relaxation, and listening to a Story.

3.4.2.1 Self-reported rumination measures: VAS scores

Posterior means and 95% HDIs of the VAS scores in each condition of experiment 2 are represented in Figure XX and Table XX.

In order to compare the effects of the two kind of relaxation on the VAS scores, we then used the hypothesis() function of the brms package that allows deriving evidence ratios (ER). These evidence ratios are simply the posterior probability under a hypothesis (e.g., the hypothesis that the Orofacial relaxation session would be more effective in reducing self-reported rumination than the Arm relaxation session) against its alternative (Bürkner, 2018).

Since the Problems and the Brooding scales seemed to be sensitive markers of rumination (as their scores increased after induction in Experiment 1), our analyses were focused on these two scales.

Concerning the Problems VAS, the decrease observed in the Orofacial condition was more pronounced than in the Arm condition (Est = 11.06, SE = 6.35, ER10 = 22.65), and slightly more pronounced compared to the Story condition (Est = 6.05, SE = 6.31, ER10 = 4.98). The observed on the Brooding VAS score in the Orofacial condition was larger than

in the Arm condition ($\text{Est} = 9.98$, $\text{SE} = 6.07$, $\text{ER10} = 18.85$), and slightly more important compared to the Story condition ($\text{Est} = 5.23$, $\text{SE} = 6.01$, $\text{ER10} = 4.27$).

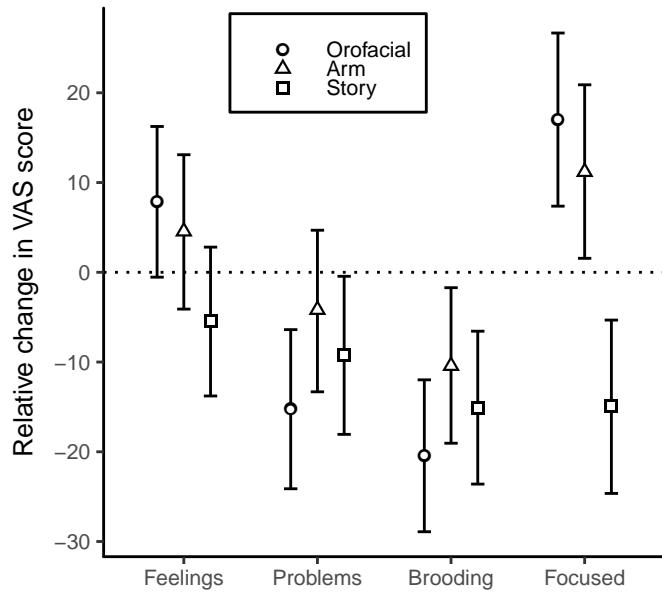


Figure 3.3: Posterior mean and 95% credible intervals for the VAS score (expressed in relative change from post-induction level).

3.4.2.2 EMG

Posterior means and 95% HDIs of the EMG amplitude in each condition of experiment 2 are represented in Figure XX and reported in Table XX. We used the same strategy as before to compare the effects of the two kinds of relaxation on the EMG amplitudes.

Concerning the OOS, the observed decrease in the Orofacial condition was more pronounced than in the Arm condition ($\text{Est} = 0.34$, $\text{SE} = 0.14$, $\text{ER10} = 140.73$), as well as concerning the OOI ($\text{Est} = 0.35$, $\text{SE} = 0.19$, $\text{ER10} = 29.46$), while we observed no noticeable differences between the two kinds of relaxation concerning the EMG amplitude of the FRO ($\text{Est} = -0.04$, $\text{SE} = 0.14$, $\text{ER10} = 1.53$).

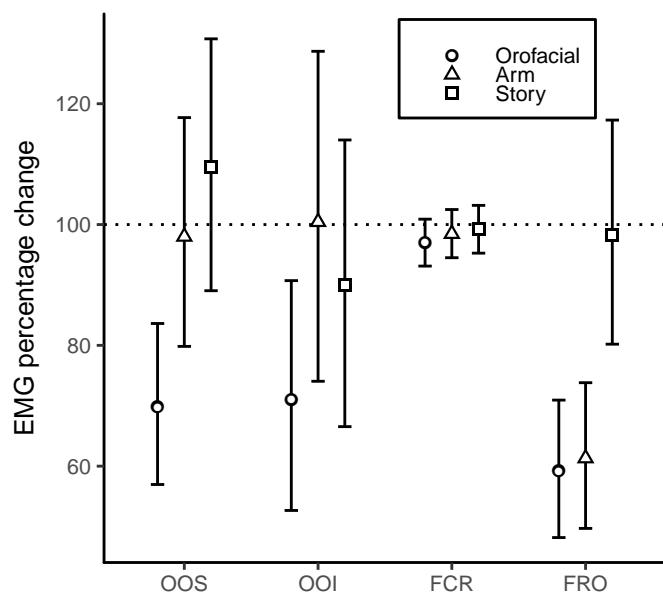


Figure 3.4: Posterior mean and 95% credible intervals for the VAS score (expressed in relative change from post-induction level).

3.5 Discussion

3.5.1 Experiment 1

In the first experiment, we examined electromyographic correlates of induced rumination in healthy individuals. According to the *Motor Simulation view*, we predicted an increase in the activity of all facial muscles after the rumination induction, associated with an increase in self-reported rumination. Alternatively, the *Abstraction view* predicted an increase in self-reported rumination associated with an increase in forehead activity with no changes in either lip or forearm activity.

To test the predictions of these two theoretical views, we compared EMG measures and VAS scores after induction to their values before induction. EMG activity was examined in four muscles: OOS and OOI, two muscles involved in speech production, FRO, a facial negative- affect-related but not speech-related muscle, and FCR, a non-facial control muscle on the non-dominant forearm.

As predicted by the *Motor Simulation view*, we observed an increase in the activity of the two speech-related muscles (OOS & OOI) as well as in the negative-affect-related muscle (FRO) and no change in FCR activity. The increase in facial EMG together with the increase in the subjective reports of rumination suggests that facial EMG increase is a correlate of verbal rumination. As supported by several studies results, the forehead muscle activity has been associated with unpleasant emotions (Jäncke et al., 1996) or anxiety (Conrad & Roth, 2007). The increase in FRO activity observed here is consistent with the increase in negative emotions induced by our negatively valenced induction procedure. *Orbicularis oris* lip muscles are associated with speech production. The increase in lip activity observed here suggests that the speech motor system was involved during the ruminative phase. The fact that the FCR remained stable after rumination induction suggests that the observed facial

activity increase was not due to general body tension induced by a negative mental state. These facial EMG results therefore support the hypothesis that rumination is an instance of articulatory-specified inner speech.

After the rumination induction, a larger increase in OOI activity was observed compared to the increase in OOS activity. This finding is consistent with previous findings of higher EMG amplitude in the lower lip during speech and inner speech (e.g., Barlow & Netsell, 1986; Regalo et al., 2005; Sokolov, 1972) or auditory verbal hallucinations (Rapin et al., 2013a). Rapin et al. (2013a) have explained the difference between the activities of the two lip muscles by muscle anatomy. The proximity of the OOI muscle with other speech muscles (such as the depressor angularis muscle or the mentalis) could increase the surface EMG signal captured on the lower lip (OOI), as compared to the upper lip (OOS) during speech. An even larger increase in FRO activity was observed compared to the increase in lip muscle activity. As EMG amplitude is known to vary with muscle length (Babault et al., 2003), the greater increase in frontalis activity could be explained by its anatomical properties.

However, although a functional distinction can be drawn between the forehead and the lip muscles, one should acknowledge the fact that these two sets of muscles can be commonly activated during some behaviours. For instance, Boxtel & Jessurun (1993) have shown that orbicularis oris inferior and frontalis were both activated during a two-choice serial reaction task in which nonverbal auditory or visual signals were presented. Moreover, there was a gradual increase in EMG activity in these muscles during the task, either when the task was prolonged or when the task was made more difficult. They interpreted this increase in EMG activity as associated with a growing compensatory effort to keep performance at an adequate level. An alternative interpretation is that the increase in task difficulty was dealt with by inner verbalization. Covertly rehearsing the instructions or covertly qualifying the stimuli might have helped the participants to perform adequately. Therefore, the increase in orbicularis oris activity might have been related to an increase in covert verbalization, whereas the increase in frontalis activity might have been related to increased anxiety or tension. The fact that the EMG increase was muscle specific, and that some facial muscles (*orbicularis oculi*, *zygomaticus major*, *temporalis*) did not show an increase in activity unless the task became too difficult, supports this interpretation. It cannot be ruled out, however, that orbicularis oris activity may in some cases be related to mental effort without mental verbalisation. Nevertheless, although the I.Q. test itself was designed to induce mental effort, no cognitively demanding task was asked to the participant during the period of EMG recording (i.e., approximately four minutes after the end of the test). Although we cannot absolutely exclude that rumination in itself could require cognitive effort, it seems unlikely that mental effort was the main factor of variation.

Scores on the VAS need to be discussed in further detail. We examined which VAS scales were most suitable to capture changes in state rumination to allow focused analyses. Due to the “pre-baseline” relaxation session, during which participants were asked to concentrate on their body and breathing cycles, participants reported a high level of attentional self-focus at baseline (“Feelings” and “Focused” VAS). Because of the high level of self-focused attention at baseline, it is likely that the scores on the “Feelings” and “Focused” VAS did not show the expected increase after rumination induction (ceiling effect). The scores on the scales “Problems” and “Brooding”, which are more representative of maladaptive rumination, did increase after our rumination induction paradigm, however. Interestingly, the “Brooding” VAS corresponded to a larger increase and seemed to be more sensitive to rumination induction than the “Problems” VAS. Given this greater sensibility and the strong positive correlation between the “Brooding” and the “Problems” VAS, it

thus make sense to consider the “Brooding” VAS as a better estimate of ruminative state, at least within our paradigm. We will therefore only use this scale to assess rumination in the following.

The fact that we did not observe any association between the propensity to ruminate (as measured by the Mini-CERTS questionnaire) and the effects of the induction is consistent with the results of Rood, Roelofs, Bögels, & Arntz (2012) who found that the level of trait rumination did not moderate the effects of a rumination induction.

3.5.2 Experiment 2

In the second experiment, we studied the effects of two muscle-specific relaxation sessions: Orofacial relaxation and Arm relaxation. We compared their effects to a third control condition (Story), which did not involve the deliberate relaxation of any specific muscle. Our predictions were that a decrease in facial EMG activity should be observed in each condition. If the *Motor Simulation view* is correct, we expected a larger decrease in the activity of all facial muscles in the “Orofacial relaxation” condition than in the “Arm relaxation” condition, associated with a larger decrease in self-reported rumination. Additionally, we expected a more pronounced decrease in the two relaxation conditions (orofacial and arm relaxation conditions) than in the control (“Story”) condition. We also expected no difference between relaxation conditions regarding the change in the forearm muscle activity.

The data indicated a decrease in self-reported rumination (“Brooding” VAS) in each condition. The “Orofacial” relaxation condition elicited a slightly larger decrease than the “Arm relaxation” or the “Story” condition. However, there was extensive individual variation in response to these conditions. As concerns EMG results, we observed a decrease in OOS and OOI activities in all three conditions but this decrease was more pronounced in the orofacial condition than in the other two conditions. The frontalis activity did not show the same pattern. A similar FRO activity decrease was observed in both the orofacial and the non-orofacial relaxation conditions. Therefore, in Experiment 2, the lip muscles and the forehead muscle follow differential evolutions. A dissociation was observed: whereas both orofacial and arm relaxations resulted in a decrease in forehead activity, only orofacial relaxation was successful at reducing lip activity.

Considering both VAS results and the dissociation in EMG patterns, several interpretations are possible. The first interpretation is that verbal production associated with rumination was more reduced by orofacial muscular relaxation than by non-orofacial relaxation. This interpretation is consistent with the fact that the “Brooding” VAS was slightly more decreased in this condition compared to the other two. The larger decrease in OOS and OOI amplitude after orofacial relaxation would thus reflect this reduction in verbal production, as hypothesised by the *Motor Simulation view*. The fact that FRO activity displayed a similar decrease in both orofacial and non-orofacial relaxation conditions could suggest that any means of body relaxation (be it orofacial or not) is appropriate to reduce negative affect and can therefore reduce forehead contraction. This suggests that the FRO activity increase presumably reflected negative affect and tension (such as observed in EMG studies on generalised anxiety disorder patients, see Conrad & Roth, 2007, for a review).

Alternatively, one could also argue that the larger decrease in lip muscle activity after orofacial relaxation finds a more trivial explanation in that it seems obvious to expect that orofacial relaxation will be more efficient to reduce lip muscle contraction than non-orofacial relaxation. Thus, the different impacts of the two relaxation sessions

on the lip muscles would not be related to reduced rumination per se but simply to a more anatomically targeted relaxation. However, several observations argue against such an interpretation. The larger decrease in the “Brooding” VAS in the orofacial relaxation condition compared with the other conditions suggests that the reduction in lip muscle activity is indeed related to the reduction in rumination. Moreover, an interpretation solely based on anatomical links does not explain why FRO activity displayed the same amount of reduction in both relaxation sessions. If reduction in muscle activity was merely related to the effect of facial muscle relaxation, then the decrease in FRO activity should have also been higher in the orofacial relaxation condition than in the other relaxation condition, which was not the case. Therefore the dissociation between forehead and lip patterns of activity, together with the differential effects of the two types of relaxation on subjective rumination reports strongly suggest that different processes underlie the activity of these two sets of muscles. We therefore consider that the first interpretation is more plausible: frontalis activity seems related to overall facial tension due to negative affect whereas lip activity seems to be related to the specific involvement of the speech musculature in rumination. These results thus seem to confirm the interpretation of decreased OOS and OOI activities in the orofacial relaxation condition as markers of rumination reduction.

Interestingly, we observed no changes of forearm EMG activity in any of the three conditions of Experiment 2. The fact that the relaxation session focused on the forearm was not associated with a decrease in FCR activity has a simple explanation: FCR activity had not increased after rumination induction and had remained at floor level. The forearm was thus already relaxed and the Arm relaxation session did not modify FCR activity. Another interesting conclusion related to this absence of modification of forearm activity is that relaxation does not spuriously decrease muscle activity below its resting level. One possible interpretation of the increase in lip EMG after rumination induction could have been that baseline relaxation artificially decreased baseline activity under its resting level. The facts that forearm activity did not decrease after arm-focused relaxation contradicts this interpretation.

Finally, the “Story” condition was also associated with a decrease in OOI and FRO activities. This could mean that listening to a story reduced rumination to the same extent as relaxation did. However, the discrepancy observed in “Focused” VAS between the two relaxation conditions on the one hand and the control condition on the other hand, suggests that the EMG decrease observed in the “Story” condition might be attributable to a different cause than that observed in the two relaxation conditions. Listening to a story could help reducing rumination by shifting attention away from ruminative thoughts. Relaxation sessions could help reducing rumination by shifting attention to the body in a beneficial way.

3.5.3 General discussion

We set out two experiments to examine whether rumination involves motor simulation or is better described as linguistically abstract and articulatory impoverished. We used labial, facial, and arm EMG measures to assess potential articulatory correlates of rumination. The patterns of results of our study seem to be in favour of the motor nature of verbal rumination. In Experiment 1, rumination induction was associated with a higher score on the scale “I am brooding about negative things” which is representative of abstract-analytical rumination, considered as verbal rumination. This maladaptive rumination state was associated with an increase in the activity of two speech-related

muscles, without modification of the arm muscle activity, which indicates that rumination involves activity in speech articulatory muscles, specifically. The concurrent increase in forehead muscle activity could be explained by an increase in negative emotions induced by our negatively valenced induction procedure. The results of Experiment 1 therefore show the involvement of the speech musculature during rumination. This is in line with the *Motor simulation view*, according to which inner speech is fully specified at the articulatory level, not just the lexical level.

In Experiment 2, guided relaxation resulted in a decrease in speech muscle activity. In the lip muscles, the activity decrease was stronger after orofacial relaxation than after arm-focused relaxation. In the forehead muscle, however the effect was the same for both types of relaxation. This decrease in speech muscle activity was associated with a decrease in self-reports of rumination and was most pronounced after orofacial relaxation. These findings suggest that a reduction in speech muscle activity could hinder articulatory simulation and thus limit inner speech production and therefore reduce rumination. This interpretation is consistent with the *Motor Simulation view* of inner speech. Brooding-type rumination was also diminished after the arm-focused relaxation as well as after listening to a story, although less than in the orofacial relaxation. This suggests that general relaxation or distraction are also likely to reduce negative rumination. To summarize, experiments 1 and 2 are consistent with the *Motor Simulation view* of inner speech, according to which speech muscle activity is inherent to inner speech production. Experiment 1 shows the involvement of the lip musculature during brooding-type rumination. Experiment 2 suggests that brooding-type rumination could be reduced by blocking or relaxing speech muscles.

These data support the utility of labial EMG as a tool to objectively assess inner speech in a variety of normal and pathological forms. We suggest that this method could be used as a complement to self-report measures, in order to overcome limitation of these measures.

Our results should be interpreted with some limitations in mind. First, our sample consisted exclusively of women. Although this methodological choice makes sense considering the more frequent occurrence of rumination in women, further studies should be conducted to ascertain that our results may generalize to men. Second, in Experiment 1, no between-subject control condition was used to compare with the group of participants who underwent rumination induction. Thus, we cannot rule out that other processes occurred between baseline and rumination induction, influencing responding. Thirdly, substantial inter-individual differences were observed concerning the size of the effect of rumination induction on facial EMG activity. The results of Jäncke (Jäncke, 1996; Jäncke et al., 1996) can shed light on this last result. Jäncke used a similar procedure (i.e., negative mood induction using a false I.Q. test and facial EMG measurements to assess emotions), except that the experimenter was not in the room while participants performed the test and acknowledged their results. The experimenter then came back to the room and analysed participants' behaviours. Jäncke observed an increase in facial muscular activity (assessed when participants were reading their results) only in participants who were prone to express their distress when the experimenter came back, while more introverted participants did not show any increased facial activity when reading their results. Jäncke interpreted these results in the framework of an ecological theory of facial expression, suggesting that facial expressions would not only be guided by underlying emotions, but also by their communicative properties. Considering these results, it seems likely that the proneness of participants to communicate their emotions could have mediated effects of the induction on their facial EMG activity. This could partially explain the observed

inter-individual variability in facial EMG activity associated with rumination. Moreover, even though rumination is a predominantly verbal process, one cannot exclude that some of our participants experienced rumination in another modality (e.g., imagery-based rumination), which would explain their lower than average lip activity.

Thus, a logical next step is to examine qualitative factors that mediate the link between rumination and facial muscular activity. These factors (among others) could be proneness to communicate emotion or proneness to verbalize affects. Additionally, recent studies suggest a link between verbal aptitudes and propensity to ruminate. Utzl, Morin, & Hamper (2011) have observed a weak but consistent correlation between the tendency to ruminate and scores on a verbal intelligence test. Penney, Miedema, & Mazmanian (2015) have observed that verbal intelligence constitutes a unique predictor of rumination severity in chronic anxious patients. To our knowledge, the link between verbal intelligence and induced rumination has never been studied. It would be interesting to examine whether the effects of a rumination induction could be mediated by verbal intelligence, and to what extent this could influence related facial EMG activity.

In conclusion, this study provides new evidence for the facial embodiment of rumination, considered as a particular instance of inner speech. Even if more data are needed to confirm these preliminary conclusions, our results seem to support the *Motor Simulation view* of inner speech production, manifested as verbal rumination. In addition, facial EMG activity provides a useful means to objectively quantify the presence of verbal rumination.

3.6 Acknowledgements

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3.7 Supplementary data

Supplementary data associated with this article can be found at <https://osf.io/882te/>.

Summary of Chapter 3

In this first experiment we... Rumination is predominantly experienced in the form of repetitive verbal thoughts. Verbal rumination is a particular case of inner speech. According to the Motor Simulation view, inner speech is a kind of motor action, recruiting the speech motor system. In this framework, we predicted an increase in speech muscle activity during rumination as compared to rest. We also predicted increased forehead activity, associated with anxiety during rumination. We measured electromyographic activity over the orbicularis oris superior and inferior, frontalis and flexor carpi radialis muscles. Results showed increased lip and forehead activity after rumination induction compared to an initial relaxed state, together with increased self-reported levels of rumination. Moreover, our data suggest that orofacial relaxation is more effective in reducing rumination than non-orofacial relaxation. Altogether, these results support the hypothesis that verbal rumination involves the speech motor system, and provide a promising psychophysiological index to assess the presence of verbal rumination.

Blah blah...

DISSOCIATING FACIAL ELECTROMYOGRAPHIC CORRELATES OF VISUAL AND VERBAL INDUCED RUMINATION

Summary of the research...¹

4.1 Abstract

Previous research shown 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 disentangle the facial electromyographic correlates of induced rumination that were 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 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. We also hypothesised that a 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 we did not find modality-specific electromyographic correlates of rumination. Moreover, the two relaxation types were similarly efficient in reducing rumination, whatsoever the rumination modality. We discuss these results in relation with the inner speech literature, and suggest that because rumination is an habitual and automatic form of emotion regulation, it might be considered as a particularly (strongly) internalised form of inner speech.

¹This experimental chapter is a submitted manuscript reformatted for the need of this thesis. Pre-registered protocol, preprint, data, as well as reproducible code and figures are available at: <https://osf.io/c9pag/>.

4.2 Introduction

The phenomenon of inner speech has been attracting the attention of the philosophical and scientific communities for a long time. This interest might be explained by the paradox surrounding inner speech: while common to everyone and experienced on a daily basis, it is nevertheless arduous to investigate. However, much can be learned about inner speech by investigating 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 general population (Watkins, Moulds, & Mackintosh, 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 have important implications for clinical practise. Second, rumination can be induced and sustained for a relatively long period of time, making it 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) and to investigate its modality-specific electromyographic correlates.

4.2.1 Rumination: its definition, functions and consequences

Rumination can be broadly defined as unconstructive repetitive thinking about past events and current mood states (Martin & Tesser, 1996). This general definition encompasses different conceptualisations that have been proposed during the last decades. Among the most influential frameworks is the *Response Style Theory* (RST, Nolen-Hoeksema, 1991a; Nolen-Hoeksema et al., 2008). Within this theory, rumination is described as a behavioural pattern that is characterised by perseverative, repetitive and passive thoughts. 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, 1991a). 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, 1991a). Alloy, Robinson and colleagues (Alloy et al., 2000; Robinson & Alloy, 2003; Smith & Alloy, 2009) subsequently appended stress-reactive rumination to this theory, suggesting that rumination can also appear following stressful life events and before the presence of negative affect. When conceptualised in this manner, it is presumed that rumination can occur before the start of the depressive mood, whereas rumination, as conceptualised by Nolen-Hoeksema (1991a), happens as a response to depressive mood. Overall, empirical research suggest that negative affect is an essential part of the ruminative thinking process (e.g., Nolen-Hoeksema & Morrow, 1993).

Based on different factor analyses and more recent models of rumination, a distinction between harmful and helpful sub-types of rumination has been introduced (e.g., Smith & Alloy, 2009; Watkins, 2008). For instance, a distinction has been suggested between brooding and reflection (Treynor et al., 2003). Brooding relates to morose pondering along with the passive comparison of one's current circumstances and a certain standard. In contrast, ruminative reflection denotes contemplation and engagement in cognitive problem solving as a means to mitigate one's depressive symptoms. In the same vein, Watkins (2008) proposed a model for differentiating between harmful and helpful forms of repetitive thought. He argued that repetitive thoughts vary along three dimensions – valence, context

and level of construal (abstract versus concrete). By this account, depressive rumination is characterised by an abstract mode of processing that involves thinking about the causes, meaning, and consequences of feelings or events. This abstract-analytic mode is opposed to a more concrete and helpful mode of processing information focused on direct, detailed and concrete experience. The processing mode theory is supported by experimental evidence showing that an abstract-analytical mode of processing is particularly deleterious for mood and cognition (Watkins, 2008).

A certain level of overlap between rumination and related constructs such as intrusive thoughts, obsessions or worry has been recognised (e.g., Olatunji, Naragon-Gainey, & Wolitzky-Taylor, 2013; Smith & Alloy, 2009). Accordingly, rumination and worry have been suggested to represent a particular form of a broader transdiagnostic process coined as *unconstructive repetitive thinking* (Olatunji et al., 2013; Watkins, 2008), *perseverative cognition* (Brosschot, Gerin, & Thayer, 2006) or *repetitive negative thinking* (Ehring & Watkins, 2008). All forms of thinking gathered under these umbrella terms share a broad involvement of self-focused repetitive thinking about negative and self-relevant topics (De Raedt, Hertel, & Watkins, 2015). However, one the most important and robust delimitation is the one between worry and rumination. On the whole, it is suggested that worry and rumination can be distinguished by their content and by their temporal orientation (Watkins, 2008), but that the *processes* underlying them would be similar. More precisely, whereas worry is focused on problem solving and future events, (depressive) rumination is rather passive and past-oriented (Nolen-Hoeksema et al., 2008; Smith & Alloy, 2009). There are also findings suggesting that worry is typically more verbal than rumination (Lawrence, Haigh, Siegle, & Schwartz-Mette, 2018), although some studies did not find this difference (Watkins et al., 2005).

Having briefly defined the functions and consequences of rumination, we now turn to a discussion of the nature of ruminative thinking, its phenomenological properties as well as how it can be induced and measured in a controlled environment.

4.2.2 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 & Behar, 2012; Goldwin, Behar, & Sibrava, 2013; McLaughlin et al., 2007). In other words, while ruminating, individuals are most often silently talking to themselves. However, what does inner speech precisely entail is still debated (for a recent review, see Lvenbruck et al., 2018). In the present paper, we examine the *motor simulation view* of inner speech production. Under this view, inner speech (content) is proposed to be the result of a soundless mental simulation of overt speech (Jeannerod, 2006; Postma & Noordanus, 1996). More precisely, inner is conceived as (inhibited) speech motor acts that trigger –via a *simulation* or an *emulation* mechanism– multimodal sensory percepts (Lvenbruck 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). Overall, these studies show that inner speech production is usually associated with an increased activity of the speech muscles.

We recently conducted a study to examine 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. This increase in facial EMG activity as a correlate of induced rumination was taken as suggestive evidence that verbal rumination does involve the speech motor system. 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 opened the possibility 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).

Despite being predominantly experienced in a verbal modality, rumination can also be experienced as visual imagery (Goldwin & Behar, 2012; Newby & Moulds, 2012; Pearson, Brewin, Rhodes, & McCarron, 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, Thompson, & Kosslyn, 2004). It has been suggested that because rumination is usually past-oriented, it should increase access to (negative) autobiographical memories (Lyubomirsky, Caldwell, & Nolen-Hoeksema, 1998). Moreover, because autobiographical memories are often experienced as visual images, rumination should likewise include visual features (Pearson et al., 2008). Several studies have obtained results that are consistent with this claim. Among a sample of patients who were diagnosed as clinically depressed, a significant majority (94.7% and more than 70%) reported that rumination 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). Another study comparing naturally occurring depressive and anxious thoughts in a non-clinical sample, found that depressive thoughts involved more images than anxious thoughts (Papageorgiou & Wells, 1999). In addition, a recent study demonstrated that a considerable number of people experience depressive cognition in a visual form (Lawrence et al., 2018). Furthermore, this study showed that individuals with a visual depressive cognitive style reported a similar amount of rumination as individuals with a verbal style. Overall, the existing literature indicates that rumination can have visual features, despite being predominantly verbal.

There are several reasons to think this distinction is of importance. First of all, mental imagery is usually related to a greater cardiovascular activation than verbal thoughts. This is specifically the case in the stressor-focused concrete visual rumination study, for individuals with high trait rumination (Zoccola, Rabideau, Figueroa, & Woody, 2014), although a later study found higher heart rate during verbal thoughts (Woody, Smolak, Rabideau, Figueroa, & Zoccola, 2015). Authors interpreted the obtained data by connecting it with the cognitive avoidance theory (Sibrava & Borkovec, 2006). According to this theory, worry, as a primarily linguistic repetitive thought, is an avoidance response whose goal is to restrain aversive images, thus reducing somatic activation and processing of emotions. Similarly, forming negative mental visual images has been shown to lead to a greater increase in anxiety in comparison to forming negative descriptive sentences (Holmes & Mathews, 2005). Taken together, these findings suggest that different modes of rumination could have different effects on individuals. Furthermore, if rumination also has a visual quality, imagery-based

therapeutic methods could also be beneficial (Pearson et al., 2008). This idea is supported by studies showing the effectiveness of mental imagery in accessing and modifying emotion in therapy (for an overview, see Hackmann & Holmes, 2004). On the whole, investigating the verbal and visual features of rumination could contribute to sharpen our understanding of the ruminative processes and lead to better-adapted therapeutic strategies.

4.2.3 Inducing rumination in a controlled environment

Rumination can be operationalised either as a trait, a stable response style of an individual (Nolen-Hoeksema, 1991b), or as an ongoing process or a state. When considered as a trait, individual differences in rumination have been mostly investigated by the mean of questionnaires. The most widely used instrument is the Ruminative Responses Scale (RRS) of the Response Styles Questionnaire (RSQ, Nolen-Hoeksema & Morrow, 1991). Participants are asked to rate how often they encounter these thoughts or behaviours when feeling sad or depressed. The short version of the RRS questionnaire comprises two scales, reflection and brooding (Treynor et al., 2003). The psychometric characteristics of this scale as well as its relationship with depressive symptoms have been extensively studied (for a review, see Nolen-Hoeksema et al., 2008).

However, self-report measures of rumination have several shortcomings. These measurements can be vulnerable to intents and subjectivity of the participants. They rely on the evaluation of past experience and do not focus on the fact that rumination usually arises in the presence of negative emotion. On the opposite, physiological studies of rumination provide data on rumination as it occurs as well as objective data that are less predisposed to subjective influences. Physiological measures also provide an opportunity to explore underlying mechanisms and central processes (Siegle & Thayer, 2003). For this purpose, several protocols set to induce rumination have been devised.

Experimental protocols for inducing rumination usually start with provoking negative mood in participants. To this end, some researchers employed sad music (e.g., Conway, Csank, Holm, & Blake, 2000), asked participants to recall a sad event (e.g., Rood et al., 2012), or put participants in stressful and frustrating situations such as an extremely difficult IQ test (e.g., Nalborczyk et al., 2017). Another study tried to cause negative feelings by asking participants to give a speech while being evaluated, though the authors concluded that this stressor was rather mild (Zoccola et al., 2014). In the following step, rumination is induced. Most studies have employed the rumination induction procedure developed by Nolen-Hoeksema & Morrow (1993). Within this protocol, participants are asked to focus on the meanings, causes, and consequences of their current feelings for eight minutes, while being prompted with a series of sentences. Other studies used either a modified version of this protocol (e.g., Nalborczyk et al., 2017) or prompts that were self-devised, but still following the same general idea (Rood et al., 2012; Zoccola et al., 2014). Similarly, in some studies investigating the differences between worry and rumination, participants were given an explanation of what worry or rumination is and were subsequently asked to engage in it (Goldwin & Behar, 2012; McLaughlin et al., 2007).

Experimental protocols have also used different means for exploring the characteristics of the ongoing process of rumination. In some studies (e.g., Goldwin & Behar, 2012; McLaughlin et al., 2007), participants were interrupted and asked about the features and/or content of their thoughts. Other studies used questionnaires to measure the features of the ongoing cognition (Makovac et al., 2018). Among other characteristics, several studies explored how much the ongoing inner experience was verbal and visual, without

manipulating rumination modality. In a few studies, however, experimental protocols have been specifically set out to manipulate this aspect 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 (or *mentation type* as these authors refer to it) 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, Mathews, Mackintosh, & Dalgleish (2008) is quite inspiring in designing a protocol 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. Their proposed solution was to combine pictorial and verbal cues and to ask participants to integrate them into 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. Even though participants in the imagery group of Zoccola et al. (2014) reported higher levels of mental images in comparison to the participants in the verbal group, the later group 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 a recent study which has shown that participants generate visual images both in cases where they were told to visualise or to verbally think, while they have strong verbal representations only when asked to verbally think (Amit, Hoeflin, Hamzah, & Fedorenko, 2017). Amit et al. (2017) concluded that there is a difference in volitional control of verbal and visual thinking and that people have better control over inner speech than 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.

4.2.4 The present study

It has been suggested that there is a need of studies that would induce verbal or visual rumination in order to inspect how the experience of rumination in these two modalities could 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 certain shortcomings in this protocol, some of which were highlighted by the authors, such as the stress induction component. To tackle these problems, 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 about the causes, consequences of their feelings during that situation. Based on the task developed by Holmes et al. (2008),

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 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 non-verbal 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 the change in the non-speech muscles should occur similarly in both conditions, since both conditions are expected to cause negative emotions to a similar extent. Moreover, the 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.

4.3 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, Nelson, & Simonsohn, 2012). A pre-registered version of our protocol can be found online: <https://osf.io/c9pag/>.

4.3.1 Participants

Our sample included 85 female participants, ranging in age from 18 to 31 years ($M = 19.8823529$, $SD = 2.0207621$). We chose to include only female participants in the present study, for the following three 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). Third, the distribution of gender is very unbalanced in Psychology courses. Therefore, it would be practically impossible to have a well-balanced sample with respect to gender. All participants attended undergraduate Psychology programs at Univ. Grenoble Alpes. They were all native speakers of French, had no history of psychiatric or neurological disorders, speech disorders or hearing deficits. Another inclusion criterion was that participants had no 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).

4.3.2 Material

The experimental procedure was developed using the OpenSesame software (Mathôt, Schreij, & Theeuwes, 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 (ADIInstrument, PL3516) device with a sampling rate of 1926 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 participant, while the video was recorded using 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 (ADIInstrument, 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., Laurent et al., 2016; Maier-Hein, Metze, Schultz, & Waibel, 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 the neck muscles (NCK). In addition, electrodes were also placed on the *frontalis* (FRO) as an non-speech but emotion-related muscle. Finally, we positioned a sensor on the *flexor carpi radialis* (FCR) to control for general (whole body) muscle contraction.

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, Ellis, Clement, & Yoshino, 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).

4.3.3 Procedure

We formed two groups based on the modality participants were asked to ruminate in. Hereafter these groups will be referred to as *verbal* and *visual*. Participants were also divided based on the type of relaxation they were listening to, that is, an *orofacial* relaxation, or an *arm* relaxation. As a result, there were four groups in the experiment: *verbal – orofacial*, *verbal – arm*, *visual – orofacial*, and *visual – arm*.

4.3.3.1 Trait questionnaires

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.

4.3.3.2 State questionnaires

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, Mor, Chiari, & Koster, 2018), composed of eight items also presented as VASs. 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.

4.3.3.3 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 of 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, participants baseline level of state rumination, verbal and visual level of thoughts were measured using the VASs.

4.3.3.4 Imagery training

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 combine an image and a word imagining a sentence in their head, whereas participants in the *visual* group were asked to do the same, but only imagining a picture. There were two trials. After doing this task, 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.

4.3.3.5 Stress induction

Afterwards, participants took the intelligence test. 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 to not 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).

4.3.3.6 Rumination induction

When the test was done, participants were asked to think about the causes, signification 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 task, 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.

4.3.3.7 Muscle-specific relaxation

Finally, participants listened again to a guided relaxation, only this time there were two types of relaxation. One half of verbal and one half of 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 insofar as 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 much participants followed the instruction. At the end of the experiment, participants were given an exhaustive debriefing explaining the goals of the research.

4.3.4 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 excessive 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 centered to its mean and cut with respect to the three periods of interest (i.e., baseline, rumination and relaxation period), 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 and to avoid unnecessary movements, there were a lot of subtle movements (e.g., biting the lips). The blocks containing these *artifacts* were removed from the analysis. This was done by inspecting all recordings and manually removing blocks during which there were visually obvious bursts of the EMG amplitude.

4.3.5 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 induction². These analyses were conducted using the *brms* package (???, 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

²An introduction to Bayesian statistical modelling is outside the scope of the current paper but the interested reader is referred to Nalborczyk et al. (2019a), for an introduction to Bayesian multilevel modelling using the *brms* package.

the Savage-Dickey method³. These BF_s 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).

4.4 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.

4.4.1 Effects of the rumination induction and rumination modality

4.4.1.1 Descriptive statistics and figures

We represent the standardised EMG amplitude during the rumination period for each facial muscle in Figure 4.1. 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).

³This 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, Lodewyckx, Kuriyal, & Grasman, 2010).

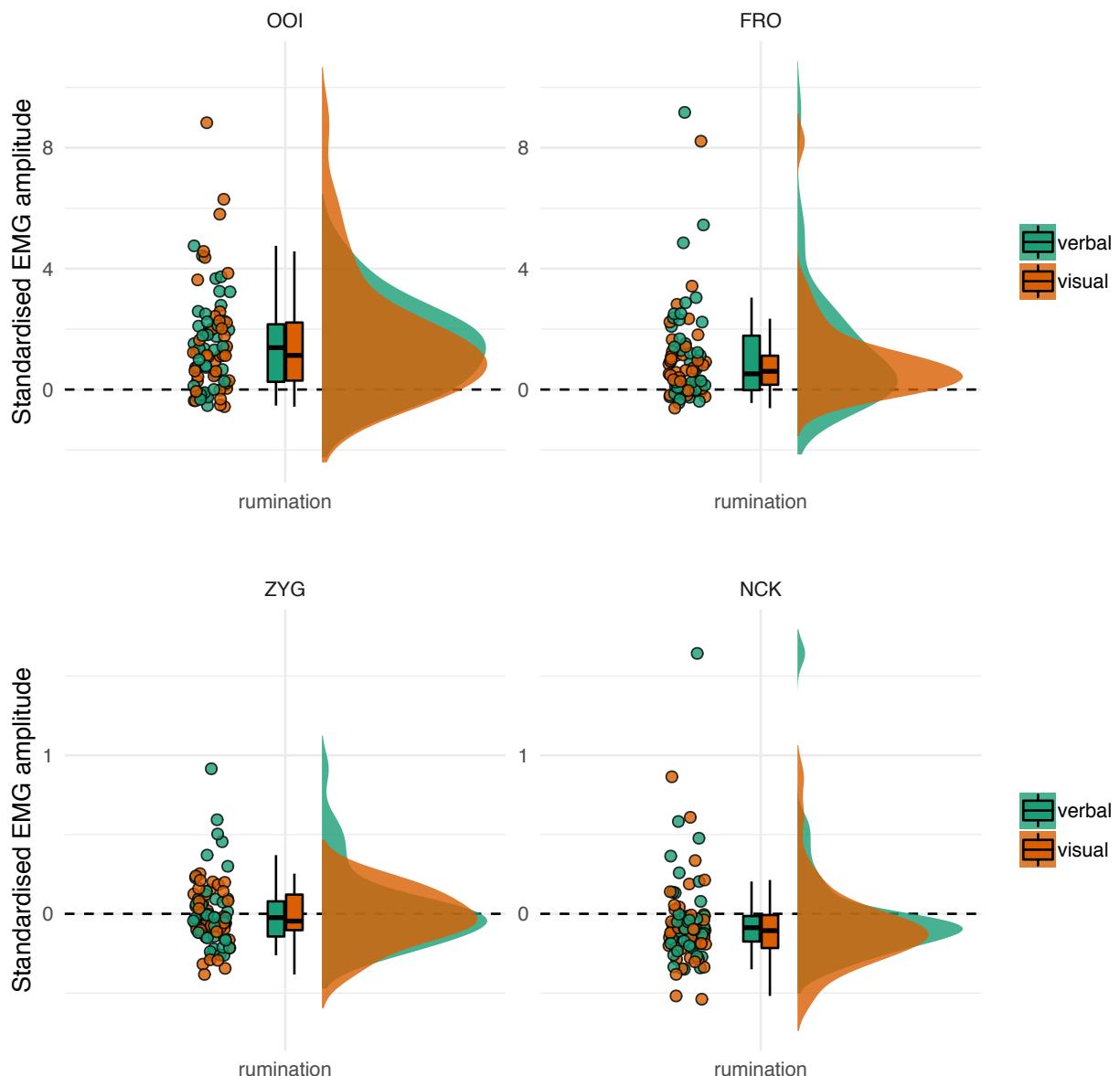


Figure 4.1: Standardised EMG amplitude during the rumination period. The coloured dots represent the mean standardised EMG amplitude by participant and by type of induction. The boxplot represents the median as well as the first and third quartiles. Note: the y-axis differs between the two rows.

4.4.1.2 Confirmatory (preregistered) analyses

In accordance with the preregistered 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 5.2.

Table 4.1: Estimates from the multivariate Gaussian model.

Response	Term	Estimate	SE	Lower	Upper	Rhat	BF01
ZYG	Intercept	-0.054	0.033	-0.120	0.011	1.000	8.251
ZYG	group	0.065	0.066	-0.066	0.193	1.000	9.332
OOI	Intercept	1.022	0.183	0.656	1.378	1.000	<0.001
OOI	group	0.209	0.341	-0.466	0.904	1.000	2.469
NEK	Intercept	-0.002	0.023	-0.050	0.043	1.000	41.497
NEK	group	0.042	0.046	-0.050	0.132	1.000	13.642
FRO	Intercept	1.504	0.184	1.131	1.861	1.000	<0.001
FRO	group	-0.178	0.346	-0.869	0.516	1.000	2.535
FCR	Intercept	-0.036	0.036	-0.107	0.037	1.000	17.464
FCR	group	0.092	0.072	-0.048	0.235	1.000	6.094

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 ($\beta = 0.209$, 95% CrI [-0.466, 0.904], $BF_{01} = 2.469$) nor on the FRO ($\beta = -0.178$, 95% CrI [-0.869, 0.516], $BF_{01} = 2.535$).

However, before to proceed 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 5.3.

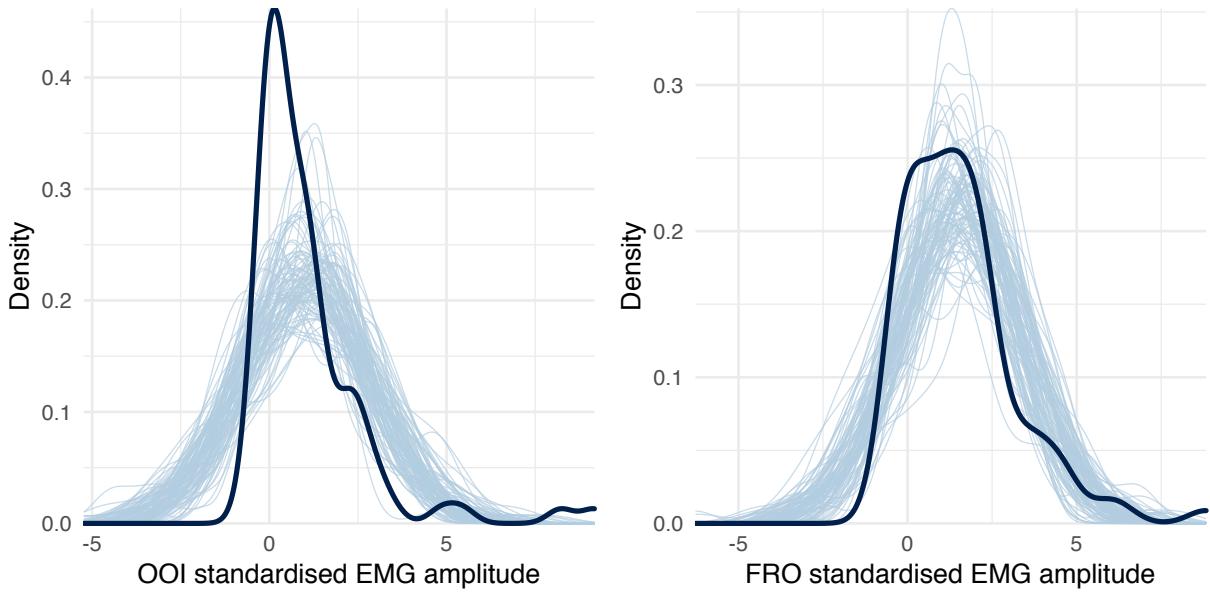


Figure 4.2: Posterior predictive checking for the first model concerning the OOI and FRO muscles. The dark blue line represents the distribution of the raw data while light blue lines are dataset generated from the posterior distribution.

4.4.1.3 Exploratory analyses

The previous figure 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 95% of their data (during the manual artefact removal step). Accordingly, these participants should weight less in the estimation of the overall effect. In the following models, we weight the importance of each participant by 1 minus the proportion of signal that was rejected for this participant⁴. Estimations from this model are reported in Table 4.2.

⁴Technically, what is weighted is the contribution of the observation to the *likelihood* function.

Table 4.2: Estimates from the multivariate (weighted) Skew-Normal model.

Response	Term	Estimate	SE	Lower	Upper	Rhat	BF01
ZYG	Intercept	-0.035	0.040	-0.112	0.048	1.000	16.401
ZYG	group	0.087	0.066	-0.045	0.220	1.000	6.443
OOI	Intercept	1.195	0.170	0.855	1.542	1.000	<0.001
OOI	group	-0.073	0.247	-0.565	0.450	1.000	4.013
NEK	Intercept	-0.005	0.031	-0.065	0.058	1.000	31.357
NEK	group	0.026	0.054	-0.084	0.131	1.000	16.084
FRO	Intercept	1.537	0.210	1.133	1.968	1.000	<0.001
FRO	group	-0.030	0.313	-0.700	0.588	1.000	3.194
FCR	Intercept	0.003	0.040	-0.076	0.087	1.000	24.682
FCR	group	0.111	0.071	-0.026	0.257	1.000	4.109

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 ($\beta = -0.073$, 95% CrI [-0.565, 0.45], $BF_{01} = 4.013$) nor on the FRO ($\beta = -0.03$, 95% CrI [-0.7, 0.588], $BF_{01} = 3.194$). The posterior predictive checks for this model are presented in Figure 4.3 and indicate that this model seems to better accommodate the specificities of the collected data.

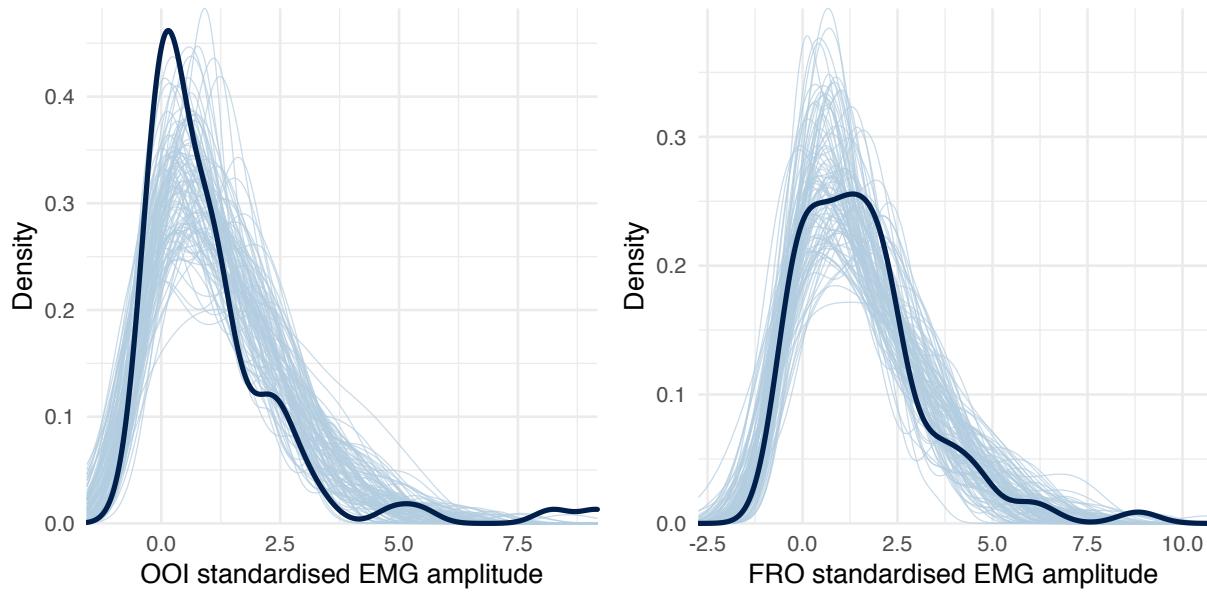


Figure 4.3: Posterior predictive checking for the Skew-Normal model concerning the OOI and FRO muscles. The dark blue line represents the distribution of the raw data while light blue lines are dataset generated from the posterior distribution.

4.4.1.3.1 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 4.3.

Table 4.3: 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	87.45 (2.86)	31.67 (4.38)	44
visual	83.92 (4.04)	30 (4.53)	41

Considering that both groups showed a similar ratio of verbal/non-verbal thoughts (see Table 4.3), we used these self-reports to define a posteriori 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 have been used to assess the amount of verbal and non-verbal thoughts during the rumination period (see Figure 4.4).

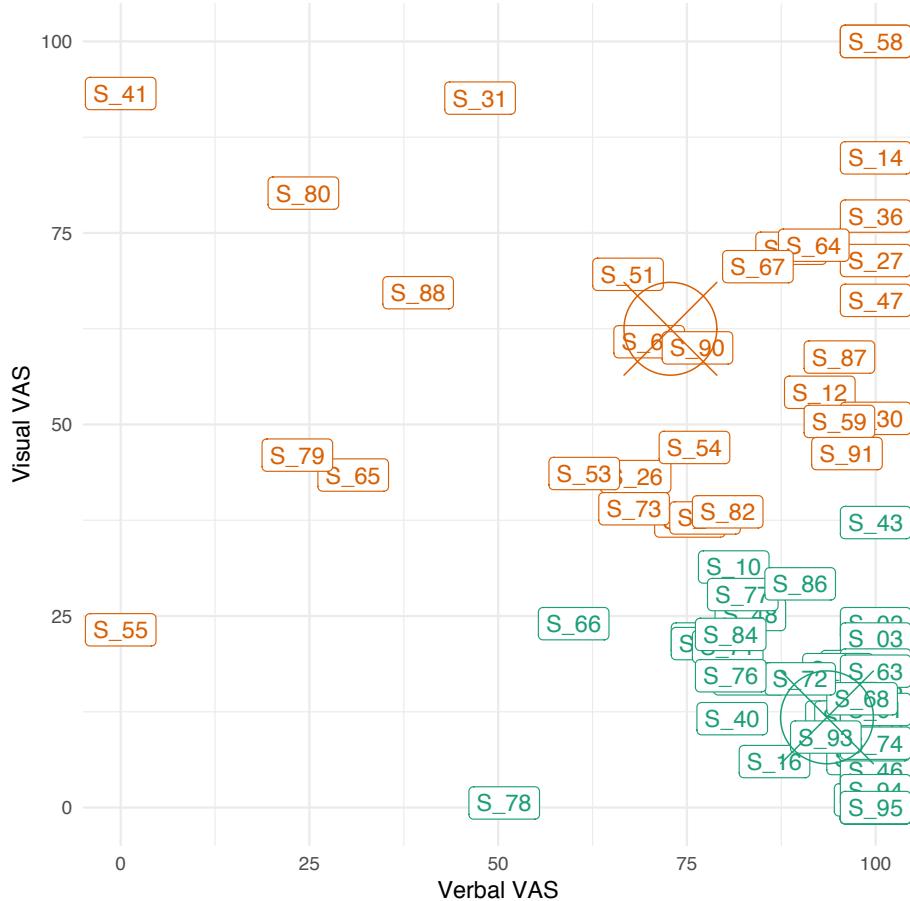


Figure 4.4: Results of the cluster analysis. The centroid of each cluster is represented by a circle and a central cross. The green cluster represents 'verbal ruminators' while the orange one represents 'non-verbal ruminators'.

As can be seen from Figure 4.4 and from Table 4.4, 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.

Table 4.4: Center and size (number of participants) of the two clusters identified by the k-means algorithm.

Cluster	Verbal VAS	Visual VAS	Size
1	93.55	11.77	53
2	72.81	62.49	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 each muscle's standardised EMG amplitude. Estimations from this model are reported in Table 5.3 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 4.5: Estimates from the multivariate (weighted) Skew-Normal model based on the k-means clusters.

Response	Term	Estimate	SE	Lower	Upper	Rhat	BF01
ZYG	Intercept	-0.032	0.041	-0.110	0.053	1.000	17.005
ZYG	cluster	-0.005	0.069	-0.148	0.131	1.000	14.664
OOI	Intercept	1.196	0.174	0.855	1.553	1.000	<0.001
OOI	cluster	-0.037	0.253	-0.571	0.485	1.000	3.915
NEK	Intercept	0.004	0.031	-0.056	0.066	1.000	32.501
NEK	cluster	-0.071	0.052	-0.177	0.037	1.000	7.382
FRO	Intercept	1.626	0.210	1.210	2.047	1.000	<0.001
FRO	cluster	-0.584	0.348	-1.302	0.102	1.000	0.708
FCR	Intercept	0.004	0.042	-0.078	0.090	1.000	24.173
FCR	cluster	0.018	0.073	-0.127	0.163	1.000	13.835

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.

4.4.1.3.2 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 4.5. 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 not substantial relation concerning the other muscles.

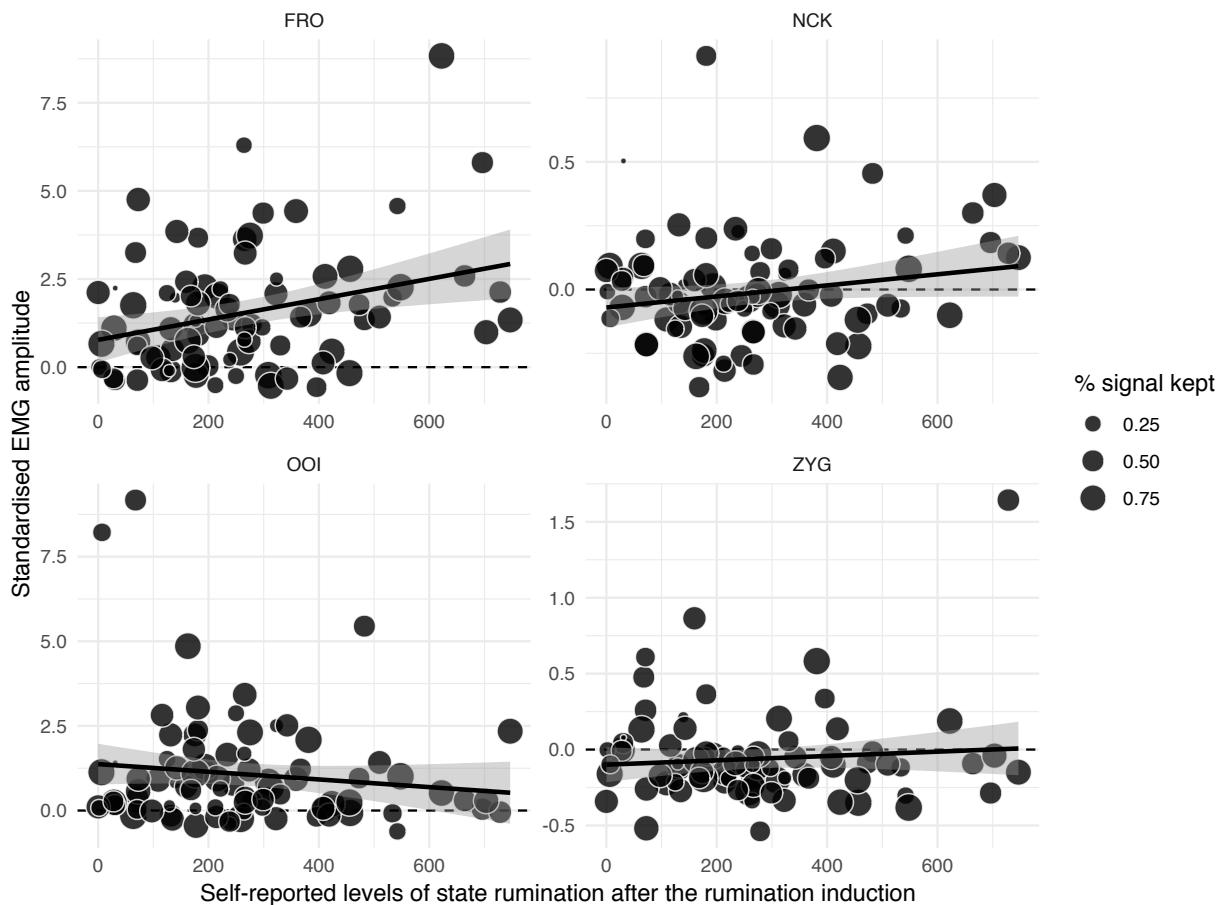


Figure 4.5: Relation between self-reported levels of state rumination (on the x-axis) and standardised EMG amplitude after the rumination induction (on the y-axis). The dots represent individual observations, whose size varies with the percentage of signal that was kept after removing artefacts. The black line represents the regression line 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 4.6.

Table 4.6: 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
ZYG	Intercept	-0.032	0.041	-0.112	0.051	1.000	17.092
ZYG	bsri	0.004	0.034	-0.061	0.070	1.000	29.882
OOI	Intercept	1.187	0.170	0.860	1.536	1.000	<0.001
OOI	bsri	-0.063	0.130	-0.321	0.195	1.000	7.061
NEK	Intercept	-0.006	0.030	-0.063	0.058	1.000	33.05
NEK	bsri	0.030	0.030	-0.027	0.092	1.000	19.442
FRO	Intercept	1.523	0.208	1.126	1.957	1.000	<0.001
FRO	bsri	0.283	0.192	-0.097	0.660	1.000	1.805
FCR	Intercept	0.000	0.041	-0.079	0.086	1.000	24.845
FCR	bsri	0.048	0.035	-0.023	0.116	1.000	11.079

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 ($\beta = 0.283$, 95% CrI [-0.097, 0.66], $BF_{01} = 1.805$). 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 a posteriori groups of verbal vs. non-verbal ruminators, we did not find 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).

4.4.2 Effects of the relaxation

4.4.2.1 Planned (preregistered) analyses

We hypothesised that an orofacial relaxation should 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 4.7.

Table 4.7: Estimated changes in self-reported levels of state rumination (BSRI scores).

Term	Estimate	SE	Lower	Upper	Rhat	BF01
Intercept	-92.07	13.72	-119.37	-64.96	1.00	<0.001
group	0.94	27.06	-50.68	55.06	1.00	3.69
relax_type	25.09	26.75	-29.34	76.67	1.00	2.405
group:relax_type	25.45	47.88	-73.75	118.19	1.00	1.846

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 ($\beta = -92.069$, 95% CrI [-119.371, -64.96], $BF_{01} < 0.001$) 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 4.6. This Figure supports the conclusion that we did not observe any interaction effects (the line were parallel and with similar slopes across panels).

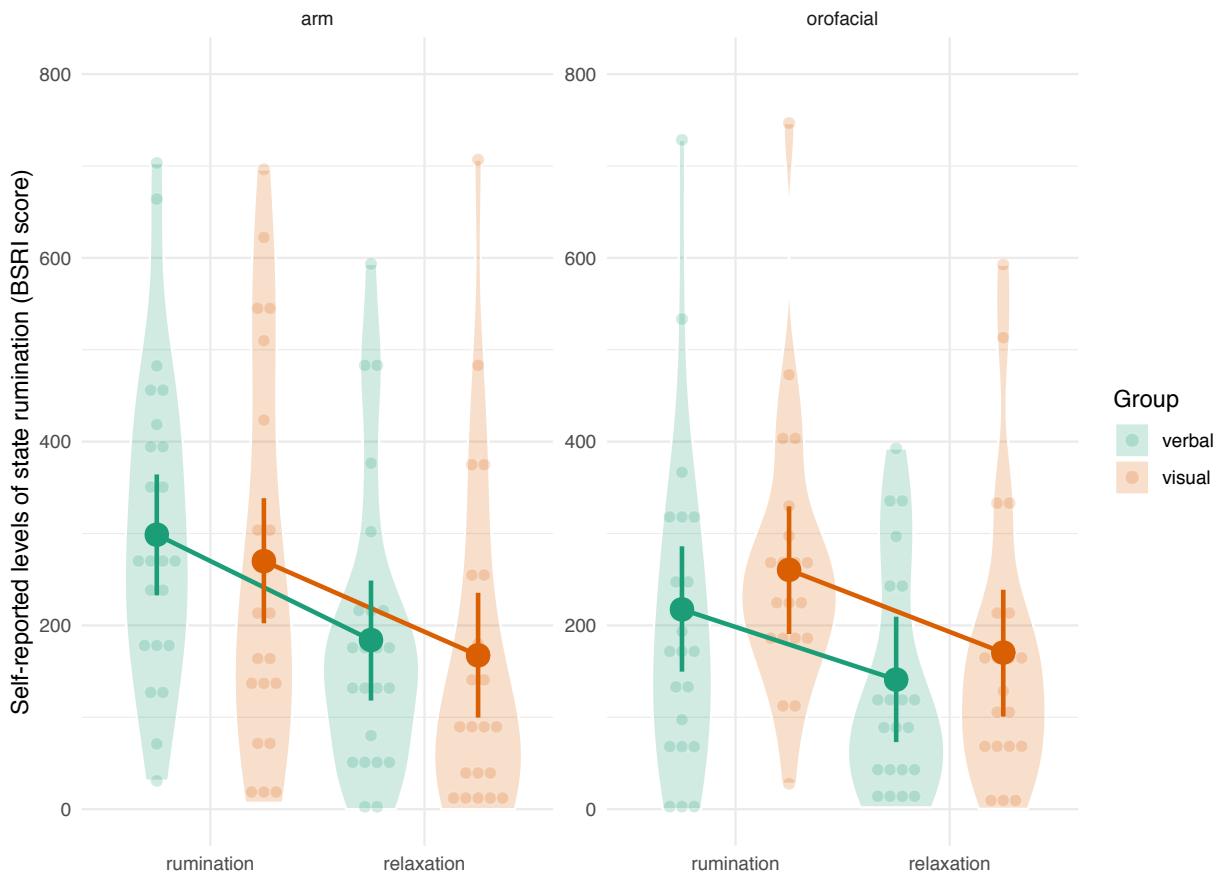


Figure 4.6: Self-reported levels of state rumination (BSRI score) by condition. The left panel depicts results in the orofacial relaxation group while the right panel depicts results in the arm relaxation group. Verbal ruminators are represented in green whereas non-verbal ruminators are represented 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 4.7) indicates that the interaction between condition (time) and the type of relaxation was slightly different according to the type of induction type ($\beta = 25.447$, 95% CrI [-73.748, 118.19], $BF_{01} = 1.846$). 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 the self-reported levels of state rumination. We turn now to a general summary and discussion of the overall results.

4.5 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 i) rumination as a kind of inner speech or ii) rumination as a state of pondering on negative affects. 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 imagery 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 affects. Following the *motor simulation view* as well as previous observations (Nalborczyk et al., 2017), we also hypothesised that a 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 (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 vs. non verbal thoughts, and no substantial difference in the facial EMG correlates across conditions. Moreover, even when defining groups of verbal vs. non-verbal ruminators *a posteriori* (i.e., based on the self-reports), these two groups were not discriminable by their facial EMG recordings. 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 (either 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.

4.5.1 Inducing rumination in different modalities

Based on the self-reports of verbal and visual thoughts assessed at the end of the rumination period (see Table 4.3), we observed that the verbal rumination induction resulted in slightly higher levels of verbal thoughts than the non-verbal rumination induction. However, both types of induction resulted in similar levels of visual mental images. These results are consistent with those of Amit et al. (2017), showing an asymmetry between inner speech and visual imagery. More precisely, they observed that inner speech production (covertly generating a sentence) was systematically accompanied by visual images. However, producing visual images was less likely to be accompanied by inner speech. Therefore, we might speculate that although it seems possible to induce verbal rumination without inducing visual rumination (and therefore to manipulate levels of verbal rumination while keeping constant levels of visual rumination), it might not be possible to induce visual rumination without inducing verbal rumination.

However, the fact that we did not find modality-specific electromyographic correlates of rumination when contrasting *a posteriori* groups of participants still poses a challenge to the *motor simulation view*. In a recent attempt to bridge response styles theories of trait rumination (Nolen-Hoeksema, 1991a) 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).

Interestingly, habitual behaviours are more automatic than non-habitual behaviours, are less conscious content 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 (Lvenbruck 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 (Lvenbruck, 2018). More precisely, highly intentional 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 less intentional 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.

As such, we might actually not expect to observe peripheral muscular activity during rumination. If this hypothesis is correct, 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 only the activity of the *frontalis* (FRO) was related to self-reported levels of state rumination (although this relation was rather weak), it is difficult to assume that the activity of the other muscles was related to rumination per se. In addition, the lack of a proper control condition (e.g., a distraction condition) prevents any causal conclusion to be drawn. Therefore, the most straightforward explanation may be that the increase in EMG amplitude recorded over the OOI might only appear in contrast to the relaxation state induced at baseline.

Finally, another explanation for the absence of modality-specific EMG correlates might come from 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 about 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, Kapur, & Maes (2018) developed a wearable device composed of seven surface EMG sensors that can attain a 92% median classification accuracy in discriminating internally vocalised digits. However, these different results be explained by differences in the research methodology employed by these different teams (see discussion in Nalborczyk et al., *in preparation*). Indeed, the between-subject

nature of the designs investigating the effects of induced rumination might hamper the possibility of highlighting modality-specific EMG correlates of induced rumination. 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.

4.5.2 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 relaxation⁵ (cf. Table 4.7 and Figure 4.6). 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 $\delta = -0.498$ (95% CI [-1.095, 0.098]) in Nalborczyk et al. (2017) and of $\delta = 0.217$ (95% CI [-0.216, 0.65]) in the current article. Because the current study 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 ($\delta = -0.052$).

⁵Neither 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.

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 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 et al., *submitted*).

4.5.3 Conclusions

We aimed to evaluate 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 induce 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. non-verbal ruminators. 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 a somehow 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 an 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 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 explained by and incorporated into integrative neurocognitive models of inner speech production.

4.6 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), as well as the glue and tidyverse packages for code writing and formatting (Hester, 2017; Wickham, 2017).

4.7 Acknowledgements

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Summary of Chapter 4

Blah blah...

MUSCLE-SPECIFIC ELECTROMYOGRAPHIC CORRELATES OF INNER SPEECH PRODUCTION

Summary of the research...¹

5.1 Abstract

Although having a long history of scrutiny in experimental psychology, it is still controversial whether inner speech (covert speech) production is accompanied by peripheral muscular activity in the speech muscles. We address this question by briefly reviewing previous findings related to the phenomenon of inner speech and to the broader phenomenon of motor imagery. We then present the results of a preregistered experiment looking at the electromyographic correlates of both overt speech and inner speech production of two classes of nonwords. An automatic classification approach was undertaken to discriminate these signals according to the class of nonword to be uttered. Although this approach lead to reasonable accuracy rates during overt speech production, it failed to discriminate inner speech content based on surface electromyography signals. We discuss these results in relation to other recent results and suggest alternative ways to test the engagement of the speech motor system during inner speech production. Pre-registered protocol, preprint, data, as well as reproducible code and figures are available at: <https://osf.io/czer4/>.

5.2 Introduction

As you read these words, you are likely experiencing the presence of a familiar speechlike companion. This inner voice usually accompanies daily activities such as reading or writing and is estimated to be present at least one quarter of our awaken life (Heavey & Hurlburt, 2008). By deliberately paying attention to this voice, one can examine its phenomenological properties such as identity (whose voice is it ?) or other high-level characteristics (e.g., is it

¹This experimental chapter is a submitted manuscript reformatted for the need of this thesis. Pre-registered protocol, preprint, data, as well as reproducible code and figures are available at: <https://osf.io/czer4/>.

gendered ?). It is also possible to examine lower-level features like the tone of the voice, its pitch or its tempo.

This first set of basic observations leads to some important insights about the nature of inner speech. First, if we can think about inner speech, then it should be something different from thinking itself. Second, the simple fact that we can make sensory judgements about our inner voice tautologically reveals that inner speech is accompanied by sensory percepts (e.g., speech sounds, kinaesthetic feelings). This leads to other fundamental questions: where do these percepts come from ? Why do they look like the one we experience when we *actually* (overtly) speak ?

Two main classes of explanatory models have been suggested to answer these questions. A first class of theories is described under the umbrella term of *motor simulation view*. These theories broadly suggest that inner speech can be conceived as a kind of action on its own (Jones & Fernyhough, 2007; Martínez-Manrique & Vicente, 2015) in the same way as overt speech is, except that speech percepts (e.g., speech sounds) are simulated. Most theories under this view share the postulate that the speech motor system is involved (to some extent) during inner speech production. In contrast, a second class of theories, that we describe as the *abstraction view*, suggest that inner speech results from the activation of abstract linguistic representations (e.g., Oppenheim & Dell, 2008) that do not involve lower-level features (e.g., articulatory representations).

Previous research have demonstrated that it is possible to record muscle-specific electromyographic correlates of inner speech (e.g., McGuigan & Dollins, 1989; McGuigan & Winstead, 1974). However, these studies mostly focused on small samples of children and sometimes used invasive intramuscular electromyography. In contrast, more recent research using surface electromyography in adult samples lead to mixed results (e.g., Meltzner et al., 2008). Building upon previous work, we describe an experimental set-up using surface electromyography with the aim of testing the involvement of the speech motor system during inner speech production.

5.3 Inner speech as motor imagery of speech

Speech production is an incredibly complex motor action, involving the fine-grained coordination of more than 100 muscles in the upper part of the body (Simonyan & Horwitz, 2011). In adult humans, its covert counterpart (i.e., *inner speech* or *verbal imagery*) has developed to support a myriad of different functions. In the same way as visual imagery permits to mentally examine visual scenes, *verbal imagery* can be used as an internal tool, allowing –amongst other things– to rehearse or to prepare past and future conversations (for review, see Alderson-Day & Fernyhough, 2015; Perrone-Bertolotti et al., 2014). Because speech production results from sequences of motor commands which are assembled to reach a given goal, it belongs to the broader category of motor actions (Jeannerod, 2006). Therefore, a parallel can be drawn between verbal imagery and other forms of motor imagery (e.g., imagined walking or imagined writing). Accordingly, studies on the nature of inner speech might benefit from insights gained from the study of motor imagery and the field of motor cognition (e.g., Haggard, 2005; Jeannerod, 2006).

Motor imagery can be defined as the mental process by which one rehearses a given action, without engaging in the physical movements involved in this particular action. One of the most influential theoretical explanation of this broad phenomenon is the *motor simulation theory* (MST; Jeannerod, 1994, 2001, 2006). In this framework, the concept of

simulation refers to the “offline rehearsal of neural networks involved in specific operations such as perceiving or acting” (Jeannerod, 2006, p. 29) and motor imagery is conceptualised as a simulation of the covert stage of the same executed action (O’Shea & Moran, 2017). The MST shares some similarities with the theories of embodied and grounded cognition (Barsalou, 2008) in that both account for the phenomenon of motor imagery by appealing to a simulation mechanism. However, the concept of simulation in grounded theories is assumed to operate in order to achieve a particular abstract knowledge (O’Shea & Moran, 2017), which is not the concern of the MST. In other words, we should make a distinction between *embodiment of content*, which concerns the conceptual content of language, and *embodiment of form*, which concerns “the vehicle of thought”, that is, proper speech production (Pickering & Garrod, 2013).

A second class of explanatory models of motor imagery are concerned with the phenomenon of *emulation* and with *internal models* (see Gentsch et al., 2016, for a review of the similarities and dissimilarities between simulation and emulation models). Internal model theories share the postulate that action control uses internal models, that is, systems that simulate the behaviour of the motor apparatus (Jordan & Rumelhart, 1992; Kawato, Furukawa, & Suzuki, 1987). The function of internal models is to estimate and anticipate the outcome of a motor command. Among the internal model theories, motor control models based on robotic principles (e.g., Kawato, 1999; Wolpert et al., 1995) assume two kinds of internal models (that are supposed to be coupled and regulated): a forward model (or simulator) that predicts the sensory consequences of motor commands from efference copies of the issued motor commands, and an inverse model (or controller) that calculates the feedforward motor commands from the desired sensory states (Gentsch et al., 2016; Lvenbruck et al., 2018).

Emulation theories (e.g., Grush, 2004; Moulton & Kosslyn, 2009) borrow from both simulation theories and internal model theories to posit a specific kind of simulation. In the emulation model proposed by Grush (2004), the *emulator* is a device that implements the same input-output function as the body (i.e., the musculoskeletal system and relevant proprioceptive/kinaesthetic systems)². When the emulator receives a copy of the control signal (which is also sent to the body), it produces an output signal (the emulator feedback), identical or similar to the feedback signal produced by the body, yielding mock sensory percepts (e.g., visual, auditory, kinaesthetic) during motor imagery.

By building upon models of speech motor control (e.g., Houde & Nagarajan, 2011; Wolpert et al., 1995), a recent model describes wilful (voluntary) expanded inner speech as “multi-modal acts with multi-sensory percepts stemming from coarse multi-sensory goals” (Lvenbruck et al., 2018). In other words, in this model the auditory and kinaesthetic sensations perceived during inner speech are assumed to be the predicted sensory consequences of speech motor acts, emulated by internal forward models that use the efference copies issued from an inverse model (this proposal shares similarities with the emulation model of motor imagery, Grush, 2004). It should be noted that both simulation, emulation, and motor control frameworks can be grouped under the *motor simulation view* and altogether predict that the motor system should be involved to some extent during motor imagery, and by extension, during inner speech production. We turn now to a discussion of findings related to peripheral muscular activity during motor imagery and inner speech.

²In Grush’s terminology, *emulator* is used as a synonym for *forward model* (see Grush, 2004, pp. 378–379).

5.4 Electromyographic correlates of covert actions

Across both simulationist and emulationist frameworks, motor imagery has consistently been defined as the mental rehearsal of a motor action without any overt movement. One consequence of this claim is that, in order to prevent execution, the neural commands for muscular contractions should be blocked at some level of the motor system by active inhibitory mechanisms (for a review, see Guillot et al., 2012). Despite these inhibitory mechanisms, there is now abundant evidence for peripheral muscular activation during motor imagery (for a review, see Guillot & Collet, 2005; Guillot et al., 2012, 2010). As suggested by Jeannerod (1994), the incomplete inhibition of the motor commands would provide a valid explanation to account for the peripheral muscular activity observed during motor imagery. This idea has been corroborated by studies of changes in the excitability of the motor pathways during motor imagery tasks (for a review, see Stinear, 2010). For instance, Bonnet et al. (1997) measured spinal reflexes while participants were instructed to either press a pedal with the foot or to simulate the same action mentally. They observed that both H-reflexes and T-reflexes increased during motor imagery, and that these increases correlated with the force of the simulated pressure. Using transcranial magnetic stimulation and motor evoked potentials (MEPs), several investigators observed muscle-specific increases of MEPs during various motor imagery tasks, whereas no such increase could be observed in antagonist muscles (e.g., Fadiga et al., 1999; Rossini, 1999)³.

When considered as a form of motor imagery, inner speech production is also expected to be accompanied with peripheral muscular activity in the speech muscles. This idea is supported by many studies showing peripheral muscular activation during inner speech production (e.g., Livesay et al., 1996; Locke, 1970; Locke & Fehr, 1970; McGuigan & Dollins, 1989; McGuigan & Winstead, 1974; Sokolov, 1972), during auditory verbal hallucinations in patients with schizophrenia (Rapin et al., 2013a), or during induced mental rumination (Nalborczyk et al., 2017). Some authors also recently demonstrated that it is possible to discriminate inner speech content based on surface electromyography signals with a median 92% accuracy (Kapur et al., 2018). However, other teams failed to obtain such results (e.g., Meltzner et al., 2008).

Many of these EMG studies concluded on the involvement of the speech motor system based on a difference in EMG amplitude when contrasting a period of inner speech production with a period of rest. However, as highlighted by Garrity (1977), it is usually not enough to show an increase of speech muscle activity during inner speech to conclude that this activation is related to inner speech production. Three sorts of inference can be made through electromyographic studies of inner speech production, depending on the stringency of the control procedure. The stronger sort of inference is permitted by highlighting a discriminative pattern during covert speech production, as for instance when demonstrating a dissociation between different speech muscles during the production of speech sounds of different phonemic class (e.g., contrasting labial versus non-labial words). According to Garrity (1977), other (weaker) types of control procedures include i) comparing the EMG activity during covert speech production to a baseline period (without contrasting phonemic classes in covert speech utterances), or ii) comparing the activity of speech-related and non-speech related (e.g., forearm) muscle activity. Ideally, these controls can be combined by recording and contrasting speech and non-speech related muscles in different conditions (e.g., rest, covert speech, overt speech) of pronunciation of

³As a side note, we should remark that these findings are consistent with both the simulation and the emulation views on motor imagery.

different speech sounds classes (e.g., labial versus non-labial).

Previous research carried out using the preferred procedure recommended by Garrity (1977) suggest a discriminative patterns of electromyographic correlates according to the phonemic class of the words being covertly uttered (e.g., McGuigan & Dollins, 1989; McGuigan & Winstead, 1974), which would corroborate the *motor simulation view* of inner speech. However, these studies used limited sample sizes (often less than ten participants), worked mostly with children participants and used signal processing methods that are now outdated. These factors limit the generalisability of the above findings because i) low-powered experiments provide biased estimates of effects, ii) following the natural internalisation process, inner speech muscular correlates are expected to weaken with age and iii) a higher sensitivity could be attained by using modern sensors and signal processing methods.

The present study then aims to decide between the *motor simulation view* and the *abstraction view* of inner speech, and can be seen as a conceptual replication and extension of previous works carried out by McGuigan and collaborators (e.g., McGuigan & Dollins, 1989; McGuigan & Winstead, 1974). We aimed to examine whether it is possible to demonstrate similar dissociations by using surface electromyography recorded over the lip (*orbicularis oris inferior*) and the *zygomaticus major* muscles. More precisely, if the *motor simulation view* is correct, we should observe a higher average EMG amplitude recorded over the OOI during both the overt and inner production of rounded nonwords in comparison to spread nonwords. Conversely, we would expect a lower average EMG amplitude recorded over the ZYG during both the inner and overt production of rounded nonwords in comparison to spread nonwords. In addition, we would not expect to observe content-specific differences in EMG amplitude concerning the non speech-related muscles (i.e., forehead and forearm muscles).

5.5 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 on OSF: <https://osf.io/czer4/>.

5.5.1 Participants

As previous studies of the electromyographic correlates of inner speech were mostly carried out with samples of children or young adults, used different kinds of EMG measures (surface EMG or needle EMG), and different kinds of signal processing methods, it was impractical how to determine the effect size of interest for the current study. Therefore, we used sequential testing as our sampling procedure, based on the method described in Schönbrodt & Wagenmakers (2018) and Schönbrodt, Wagenmakers, Zehetleitner, & Perugini (2017). We fixed a statistical threshold to $BF_{10} = 10$ and $BF_{10} = \frac{1}{10}$ (i.e., $BF_{01} = 10$), testing the difference between the inner production of labial items versus the inner production of non-labial items on the standardised EMG activity of the lower lip (*orbicularis oris inferior*). In order to prevent potential experimenter and demand biases during sequential testing, the experimenter was blind to BFs computed on previous participants (Beffara, Bret, & Nalborczyk, 2018). All statistical analyses have been automatized and a single

instruction was returned to the experimenter (i.e., “keep recruiting participants” or “stop the recruitment”). We fixed the maximum sample size to 100 participants.

As a result of the above sampling procedure, a total of 26 French-speaking undergraduate students in Psychology from the Univ. Grenoble Alpes took part in this experiment, in exchange for course credits⁴. They were recruited via mailing list, online student groups, and posters. Each participant provided a written consent and the present study was approved by the local ethics committee.

5.5.2 Material

5.5.2.1 EMG recordings

EMG activity was recorded using TrignoTM Mini sensors (Delsys Inc.) at a sampling rate of 1926 samples/s with a band pass of 20 Hz (12 dB/oct) to 450 Hz (24 dB/oct) and were amplified by a TrignoTM 16-channel wireless EMG system (Delsys Inc.). These sensors consist of two 5 mm long, 1 mm wide parallel bars, spaced by 10 mm, which were attached to the skin using double-sided adhesive interfaces. The skin was cleaned by scrubbing it with 70% isopropynol alcohol. EMG signals were synchronised using the PowerLab 16/35 (ADIInstrument, PL3516). Raw data from the EMG sensors were then resampled at a rate of 1 kHz and stored in digital format using Labchart 8 software (ADIInstrument, MLU60/8). EMG sensors were positioned over five muscles: the *corrugator supercilii* (COR), the *frontalis* (FRO), the *zygomaticus major* (ZYG), the *orbicularis oris inferior* (OOI), and the *flexor carpi radialis* (FCR). The two speech-related muscles (OOI and ZYG) were chosen to show content-specific EMG correlates, whereas the two non-speech related facial muscles (ZYG and FRO) were chosen to control for higher overall facial muscular activity. We also recorded the activity of the FCR of the non-dominant forearm to control for overall (whole body) higher muscular activity.

We recorded the activity of control and emotion-linked muscles (i.e., COR and FRO) that were positioned on the non-dominant side of the face (i.e., the left side for right-handed participants), while sensors recording the activity of the speech muscles (i.e., ZYG and OOI) were positioned on the dominant side of the face. As reviewed in Everdell et al. (2007), the dominant side of the face displays larger movements than the left side during speech production, whereas the non-dominant side is more emotionally expressive.

The experiment was video-monitored using a Sony HDR-CX240E video camera to track any visible facial movements. A microphone was placed 20–30 cm away from the participant’s lips to record any faint vocal production during rumination. Stimuli were displayed using the OpenSesame software (Mathôt et al., 2012) on a 19-inch colour monitor.

5.5.2.2 Linguistic material

We selected ten rounded and ten spread bi-syllabic nonwords (see Table 5.1). Each class of nonwords was specifically designed to either induce a greater activation of the lip muscle (rounded items) or a greater activation of the zygomaticus muscle (spread items). Rounded items consisted in the repetition of a syllable containing a bilabial consonant followed by a rounded vowel, whereas spread items consisted in the repetition of a syllable containing a lingual consonant followed by a spread vowel.

⁴NB: this procedure did not work optimally because we later spotted a mistake in the EMG signal processing workflow. Thus, the sequential testing stopped earlier than it should have.

Table 5.1: List of bisyllabic nonwords used in the test session.

rounded items	spread items
/mumu/	/gigi/
/pupu/	/sese/
/fofo/	/lele/
/mymy/	/sisi
/pypy/	/didi/
/byby/	/nini/
/vøvø/	/ii/*
/pøpø/	/lili/
/bøbø/	/ii/
/mm/	/gege/

Note. *Because the production of /ii/ requires a protrusion of the lips, this item theoretically slightly deviates from other items of this class.

5.5.3 Procedure

Participants were seated in front of a computer screen while audio stimuli (when applicable) were presented through speakers on both sides of the screen. A video camera was positioned on one side of the screen to monitor facial movements. After positioning of the EMG sensors, each participant underwent a relaxation session aiming to minimise pre-existing inter-individual variability on facial muscle contraction (approximate duration was 330s). This relaxation session was recorded by a trained professional sophrology therapist. Baseline EMG measurements were performed during the last minute of this relaxation period, resulting in 60s of EMG signals at baseline. Subsequently, participants went through a training session, during which they could get familiar with the main task. They trained with 8 stimuli in total (4 rounded nonwords and 4 spread nonwords)⁵. Each training stimulus appeared in three conditions (for all participants): overt speech, inner speech and listening. Nonwords to be produced (covertly or overtly) were visually presented on the screen. Then, a central fixation appeared on the screen and the participant overtly or covertly uttered the nonword. This aimed to ensure that participants were actually producing a nonword, not just simply visually scanning it. In the listening condition, the order of these two screens was reversed. A blank screen was first presented, followed by a fixation dot. The audio stimulus was presented when the fixation dot appeared, aiming to ensure that participants did not start by reading the nonword before listening to it, which could induce covert speech production. After the training, participants moved to the experimental part, that included a novel list of 20 nonwords (cf. Table 5.1). Each nonword was presented 6 times in each condition for each participant. The EMG activity was recorded during one second, after each stimulus presentation and during either production

⁵The training list can be found in the supplementary materials.

or listening. This resulted in 60 observations (60 periods of 1 second) for both classes of nonword in each test condition. The total duration of the experiment ranged between 30 min and 40 min.

5.5.4 EMG signal processing

EMG signal pre-processing was carried out using Matlab r2014a (Version 8.3.0.532, www.mathworks.fr). The EMG data were high-pass filtered at a cut-off of 20 Hz. Then, output of this first filter was sent to a low-pass filter at a cut-off of 450 Hz, in order to focus on the 20–450 Hz frequency band, following current recommendations for facial EMG studies (Boxtel, 2001; De Luca, 1997).

Although participants were explicitly asked 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 first divided the EMG signals in periods of 1 second. Then, we visually inspected audio and EMG signals recorded during each trial (a trial corresponds to one second of EMG signal). For the trials during which unwanted activity appeared, we excluded the entire 1-second trial (i.e., we did not include this trial in the final analysis, for any of the recorded muscles). This procedure lead to an average rejection rate of 16.02% ($SD = 4.91$) in the baseline condition and 13.85% ($SD = 7.54$) in the other conditions.

After pre-processing and artefact rejection, we computed the by-trial average amplitude of the centred and rectified EMG signal. This provided a score for each muscle of interest (OOI, ZYG, FRO, COR, FCR) in each condition (Baseline, Overt Speech, Inner Speech, Listening) and for each participant. 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 activity in the baseline. To normalise and standardise for baseline activity across participants, we thus expressed the EMG amplitude as a z-score from baseline activity (i.e., we subtracted the mean amplitude of the centred and rectified baseline signal and divided the result by the standard deviation of the centred and rectified baseline signal), thereafter referred to as δ .

5.5.5 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. We analysed data using *Condition* (3 modalities: speech, inner speech, and listening) and *Class* of nonwords (2 modalities, rounded and spread, contrast-coded) as within-subject categorical predictors, and the standardised EMG amplitude as a dependent variable in a multivariate (i.e., with multiple outcomes) Bayesian multilevel linear model (BMLM)⁶. In order to take into account the dependencies between repeated observations by participant, we also included in this model a varying intercept by participant. Contrary to what we pre-registered, we used a multivariate model (instead of separate models by muscle). This allowed us to estimate the correlation between each pair of muscles. Models were fitted with the *brms* package (??? and using weakly informative priors (see the supplementary materials for code details). Two Markov Chain Monte-Carlo (MCMC) chains were run for

⁶An introduction to Bayesian statistics is outside the scope of this paper. However, the interested reader is referred to Nalborczyk et al. (2019a), for an introduction to Bayesian multilevel modelling using the *brms* package.

each model to approximate the posterior distribution, including each 5.000 iterations and a warmup of 2.000 iterations. Posterior convergence was assessed examining trace plots as well as the Gelman-Rubin statistic \hat{R} . Constant effect estimates were summarised via their posterior mean and 95% credible interval (CrI), where a credible interval can be considered as the Bayesian analogue of a classical confidence interval. When applicable, we also report Bayes Factors (BFs), computed using the Savage-Dickey method, which consists in taking the ratio of the posterior density at the point of interest divided by the prior density at that point. These BFs can be interpreted as an updating factor, from prior knowledge (what we knew before seeing the data) to posterior knowledge (what we know after seeing the data).

5.6 Results

The *Results* section is divided into two parts. First, we present results from confirmatory (preregistered) analyses, aiming to test whether it is possible to dissociate the activity of the OOI and the ZYG during inner speech production, according to the content of inner speech (here, the class of nonword to be produced). More precisely, we expected an increased EMG activity of the OOI during the inner production of rounded nonwords in comparison to spread nonwords. Conversely, we expected elevated EMG activity of the ZYG during the inner production of spread nonwords in comparison to rounded nonwords. Second, we present results from exploratory (non-preregistered) analyses.

To foreshadow the results, we did not observe such a clear dissociation between the EMG activity of the OOI and the ZYG muscles, neither in the inner speech condition nor in the overt speech condition. Contrary to theoretical expectations based on phonetics and speech production theory (e.g., **Fromkin, 1966; Ladefoged & Johnson, 2006, Lieberman & Blumstein, 1989; Zemlin, 1968**), the activity of both muscles was of higher amplitude for the pronunciation of rounded nonwords (as compared to spread nonwords) during overt speech production. Additionally, the EMG amplitude on both muscles of interest was similar during the inner production (or listening) of the two classes of nonwords. However, in the *exploratory analyses* section, we report results from supervised machine learning algorithms (classification using random forests), showing a reasonable accuracy to classify EMG signals according to the class of nonwords during overt speech production. This strategy was however unsuccessful for the inner speech and the listening conditions.

Before to move to the statistical results, we represent the distribution of the whole dataset, by class, by condition and by muscle for the two main muscles of interest (OOI and ZYG) in Figure 5.1. More precisely, the first row of this figure represents the distribution of the standardised EMG scores in the inner speech condition, the second row depicts the distribution of these scores in the listening condition, whereas the third row depicts the distribution of the standardised EMG scores in the overt speech condition. The first column depicts the distribution of the standardised EMG scores recorded over the OOI muscle whereas the second one represents the distribution of the standardised EMG scores recorded over the ZYG muscle. Each individual data point is represented as a vertical bar along the x-axis of each panel whereas the vertical coloured line represents the class-specific median. Additionally, a vertical dashed line is plotted at zero, which represents the baseline level. Thus, a positive value on the x-axis represents EMG standardised scores that are higher than baseline⁷.

⁷We also created a shiny application (Chang, Cheng, Allaire, Xie, & McPherson, 2018) allowing for further visual exploration of the data by muscle, by condition, and by participant, in the 3D space formed by three

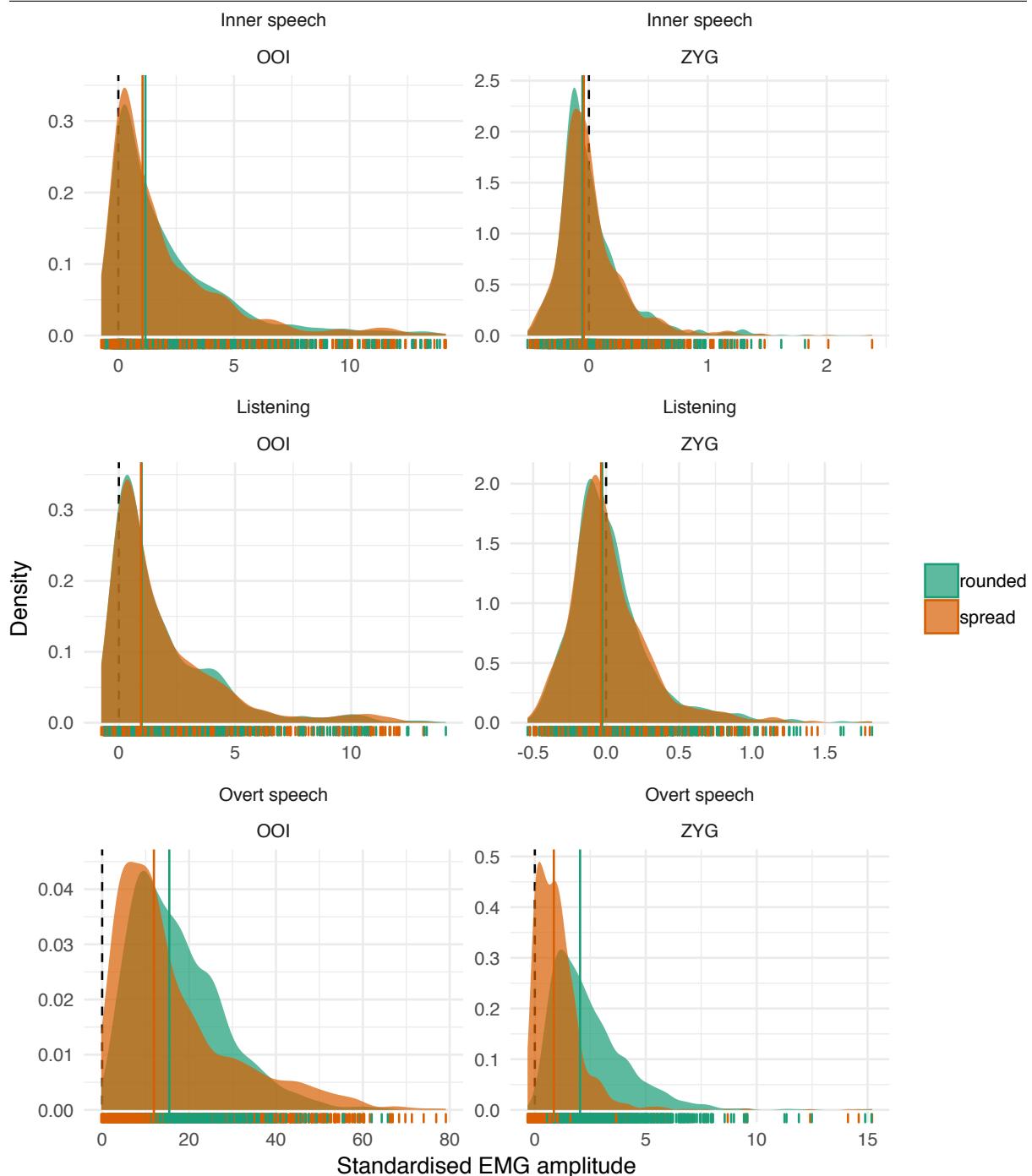


Figure 5.1: Distribution of standardised EMG scores by class and by muscle. The first row corresponds to the inner speech condition, the second one to the listening condition, and the third one to the overt speech condition. The first column depicts the EMG amplitude recorded over the OOI muscle while the second column represents the EMG amplitude recorded over the ZYG muscle. Each individual data point is represented as a vertical bar along the x-axis. The vertical coloured line represents the by-class median.

(to be chosen) muscles. This application is available online (https://barelysignificant.shinyapps.io/3d_plotly/) and the associated code is available in the OSF repository (<https://osf.io/czer4/>).

5.6.1 Confirmatory (preregistered) analyses

5.6.1.1 Bayesian multivariate multilevel Gaussian model

We then compared the standardised EMG amplitude δ for each muscle in each condition (Overt Speech, Inner Speech, Listening) by fitting a multivariate multilevel Gaussian model (as detailed previously in the Methods section). We predicted an higher increase of OOI activity during the production of rounded items in comparison to spread items and conversely, a higher increase of ZYG activity during the inner production of rounded items in comparison to spread items. These predictions should also apply to the overt speech condition (and to the listening condition). We should not observe any by-class differences of FRO and COR activity in any condition.

Table 5.2: Estimates from the Gaussian BMLM concerning the OOI and the ZYG.

Response	Term	Estimate	SE	Lower	Upper	Rhat	BF01
OOI	Inner Speech	1.87	0.42	1.02	2.66	1.00	0.02
OOI	Listening	1.73	0.37	1.03	2.48	1.00	0.00
OOI	Overt Speech	16.19	1.96	12.38	19.95	1.00	0.00
OOI	Inner Speech x Class	0.11	0.19	-0.28	0.47	1.00	43.73
OOI	Listening x Class	-0.14	0.27	-0.67	0.38	1.00	32.53
OOI	Overt Speech x Class	0.70	0.27	0.18	1.22	1.00	1.29
ZYG	Inner Speech	0.01	0.04	-0.07	0.10	1.00	237.72
ZYG	Listening	0.02	0.04	-0.06	0.10	1.00	218.90
ZYG	Overt Speech	1.77	0.22	1.32	2.23	1.00	0.00
ZYG	Inner Speech x Class	0.01	0.03	-0.05	0.06	1.00	360.68
ZYG	Listening x Class	0.00	0.04	-0.08	0.08	1.00	263.36
ZYG	Overt Speech x Class	1.35	0.04	1.27	1.42	1.00	0.00

Note. For each muscle (response), the first three lines represent the estimated average amplitude in each condition, and its standard error (SE). The three subsequent rows represent the estimated average difference between the two classes of nonwords in each condition (i.e., the interaction effect). The 'Lower' and 'Upper' columns contain the lower and upper bounds of the 95% CrI, while the 'Rhat' column reports the Gelman-Rubin statistic. The last column reports the Bayes factor in favour of the null hypothesis (BF01).

The results of this model are summarised in Table 5.2. This table reports the estimated average EMG amplitude in each condition and the corresponding BF⁸. This analysis revealed that the EMG amplitude of the OOI was higher than baseline (the standardised score was above zero) in every condition whereas it was only the case in the overt speech condition for the ZYG. Crucially, we did not observe the hypothesised difference according to the class of nonwords on the OOI during inner speech production ($\beta = 0.108$, 95% CrI [-0.281, 0.466], BF₀₁ = 43.727) nor on the ZYG ($\beta = 0.007$, 95% CrI [-0.047, 0.057], BF₀₁ = 360.677).

Figure 5.2 depicts these results by representing the distribution of the raw data (coloured dots) along with the predictions from this model. The black dots and vertical intervals represent the predicted mean and associated 95% credible interval for each class

⁸As they are not the main focus of interest here and for the sake of clarity, descriptive results for the other two facial muscles and for the forearm muscle are reported in the supplementary materials.

of non-word, each condition and for the OOI and the ZYG. Coherently with Table 5.2, this figure shows that the fitted model predicts no noticeable differences between the two classes of non-words in any condition for the OOI muscle. However, it predicts a higher average EMG amplitude associated with the rounded item as compared to the spread items in the overt speech condition for the ZYG muscle.

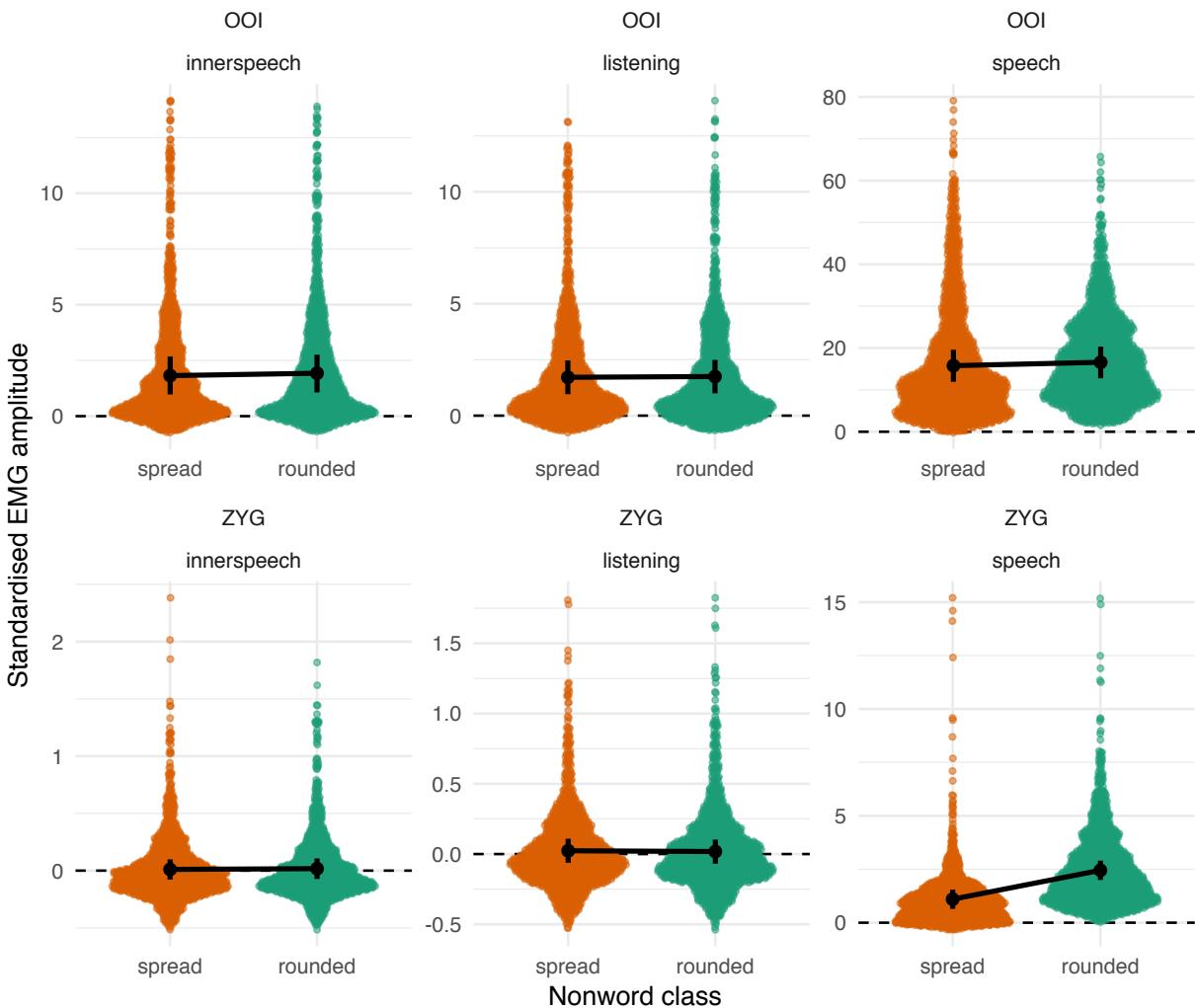


Figure 5.2: Raw data along with posterior predictions of the first model for the OOI and the ZYG muscles. Dots represent the mean prediction of this model by condition, while the vertical error bars represent the 95% credible intervals around the mean.

Before proceeding further with the interpretation of the results, it is essential to check the quality 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). The idea behind PPC is that a good model should be able to generate data that resemble the observed data (Gabry, Simpson, Vehtari, Betancourt, & Gelman, 2019). In this vein, Figure 5.3 represents the distribution of the whole dataset (across all participants and conditions) by muscle (the dark blue line) along with the distribution of hypothetical datasets generated from the posterior distribution of the model (the light blue lines). As can be seen from this Figure, the distributions of the data generated from the model differ considerably from the distribution of the observed data. Therefore, in the next section, we turn to a more appropriate model

for these data.

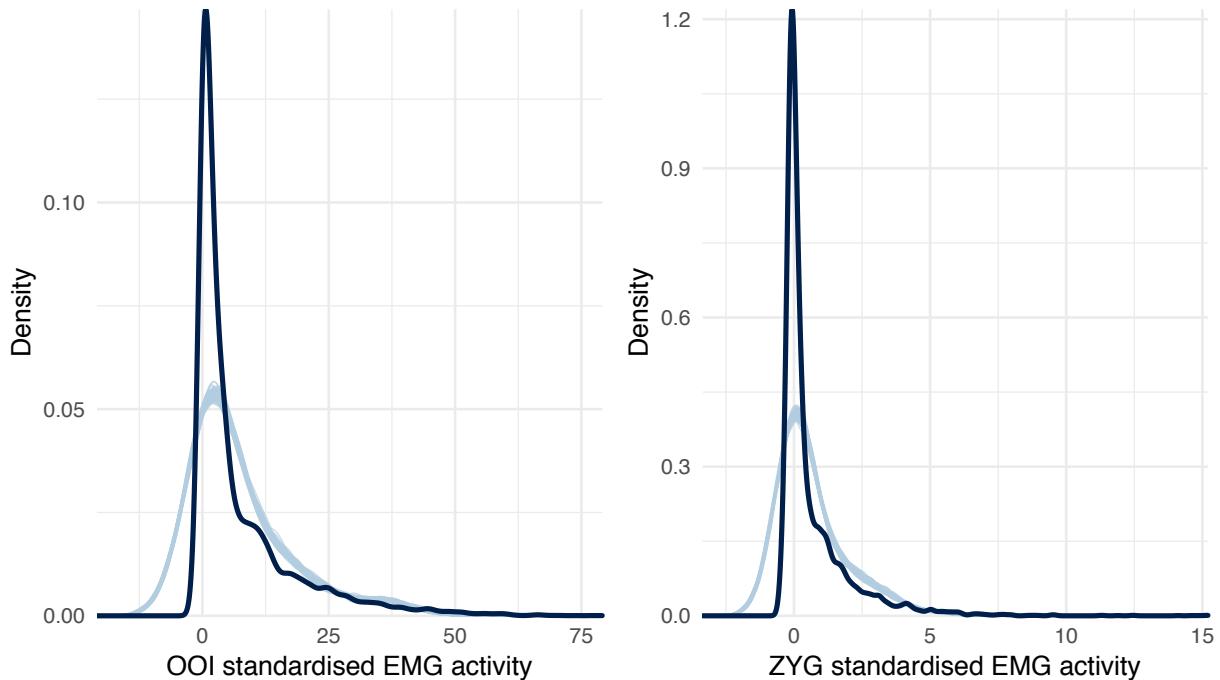


Figure 5.3: Posterior predictive checking for the first model concerning the OOI and ZYG muscles. The dark blue line represents the distribution of the raw data (across all conditions) while light blue lines are dataset generated from the posterior distribution.

5.6.1.2 Bayesian multivariate multilevel distributional Skew-Normal model

The previous figure reveals an important failure of the first model, as it fails to generate data that look like the data we have collected. More precisely, the collected data look right-skewed, as it usually happens with physiological measurements. To improve on the Gaussian model, we then assume a Skew-normal distribution for the response variable (the standardised EMG amplitude δ). 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), respectively⁹. In addition, we also improve the first model by turning it into a *distributional model*, that is, a model in which we can specify predictor terms for all parameters of the assumed response distribution (???). More precisely, we use this approach to predict both the location, the scale, and the skewness of the Skew-Normal distribution (whereas the first model only allowed predicting the mean of a Gaussian distribution). As can be seen in Figure 5.4, this second model seems better than the first one at generating data that look like the observed data.

⁹NB: the Gaussian distribution can be considered a special case of the Skew-normal distribution when $\alpha = 1$.

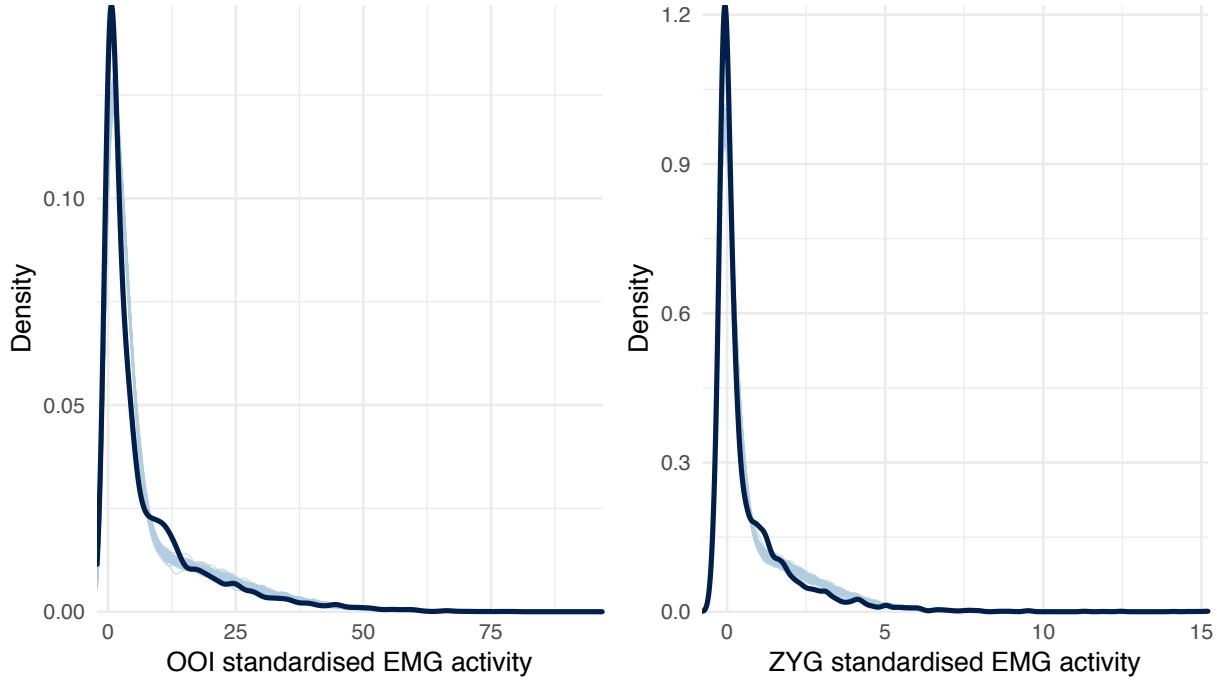


Figure 5.4: Posterior predictive checking for the Skew-Normal model concerning the OOI and ZYG muscles. The dark blue line represents the distribution of the raw data while light blue lines are dataset generated from the posterior distribution.

Table 5.3: Estimates from the distributional Skew-Normal model concerning the OOI and the ZYG.

Response	Term	Estimate	SE	Lower	Upper	Rhat	BF01
OOI	Inner Speech	2.35	0.04	2.28	2.44	1.00	0.00
OOI	Listening	2.12	0.04	2.04	2.19	1.00	0.00
OOI	Overt Speech	17.38	0.21	16.97	17.78	1.00	0.00
OOI	Inner Speech x Class	0.04	0.03	-0.02	0.10	1.00	118.39
OOI	Listening x Class	-0.02	0.04	-0.09	0.06	1.00	237.23
OOI	Overt Speech x Class	1.64	0.18	1.28	1.99	1.00	0.00
ZYG	Inner Speech	0.04	0.00	0.02	0.04	1.00	0.00
ZYG	Listening	0.04	0.01	0.03	0.05	1.00	0.00
ZYG	Overt Speech	1.91	0.02	1.86	1.95	1.00	0.00
ZYG	Inner Speech x Class	0.00	0.01	-0.01	0.02	1.00	1,089.34
ZYG	Listening x Class	0.00	0.01	-0.02	0.02	1.00	856.03
ZYG	Overt Speech x Class	0.64	0.03	0.58	0.70	1.00	0.00

Note. For each muscle (response), the first three lines represent the estimated average amplitude in each condition, and its standard error (SE). The three subsequent rows represent the estimated average difference between the two classes of nonwords in each condition (i.e., the interaction effect). The 'Lower' and 'Upper' columns contain the lower and upper bounds of the 95% CrI, while the 'Rhat' column reports the Gelman-Rubin statistic. The last column reports the Bayes factor in favour of the null hypothesis (BF01).

The estimates of this second model are summarised in Table 5.3 and Figure 5.5. According to this model, the EMG amplitude of the OOI was higher than baseline (the

estimated standardised score was above zero) in every condition whereas it was only the case in the overt speech condition for the ZYG. We did not observe the hypothesised difference according to the class of nonwords during inner speech production, neither on the OOI ($\beta = 0.043$, 95% CrI [-0.015, 0.103], $BF_{01} = 118.391$) nor on the ZYG ($\beta = 0.005$, 95% CrI [-0.011, 0.021], $BF_{01} = 1089.341$).

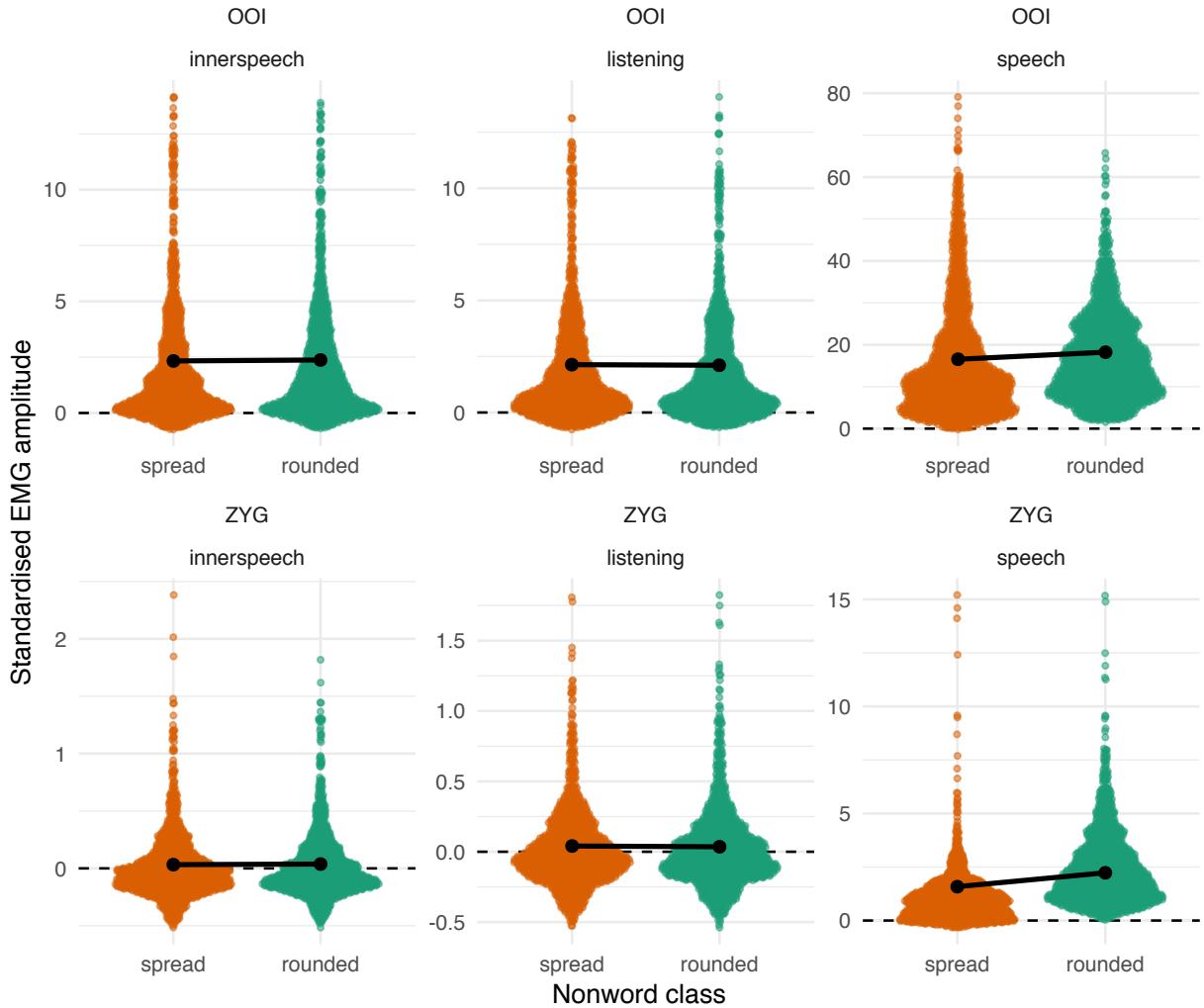


Figure 5.5: Raw data along with posterior predictions of the third model for the OOI and the ZYG muscles. Dots represent the mean prediction of this model by condition (concerning the location parameter) whereas the vertical error bars represent the 95% credible intervals.

Predictions from this model are visually represented in Figure 5.5. This figure differs from Figure 5.2 (showing the predictions of the Gaussian model) in that the second model (the Skew-normal model) predicts shifts in location for both the OOI and the ZYG muscles according the class of non-word in overt speech prediction. In contrast, the first model (the Gaussian model) predicted a by-class difference only for the ZYG muscle.

5.6.2 Exploratory (non-preregistered) analyses

In the previous section, we tried to predict the average EMG amplitude by condition on each single muscle. Although this approach was appropriate to tackle our initial research question (i.e., can we distinguish muscle-specific EMG correlates of inner speech

production?), it is not optimal to answer more general questions such as “can we predict the content of inner speech based on the available EMG data?”. In Figure 5.6, we depict the distribution of the by-word averaged EMG scores in the 2D space formed by the OOI and the ZYG muscles. This figure reveals that although different nonwords produced in overt speech seem difficult to discriminate on the basis of a single muscle (cf. Figure 5.1), it seems easier to discriminate them in the space formed by two muscles (here OOI and ZYG). More precisely, the two classes of nonwords seem to form two separate clusters in the overt speech condition, but these clusters do not seem discriminable in the inner speech or in the listening condition.

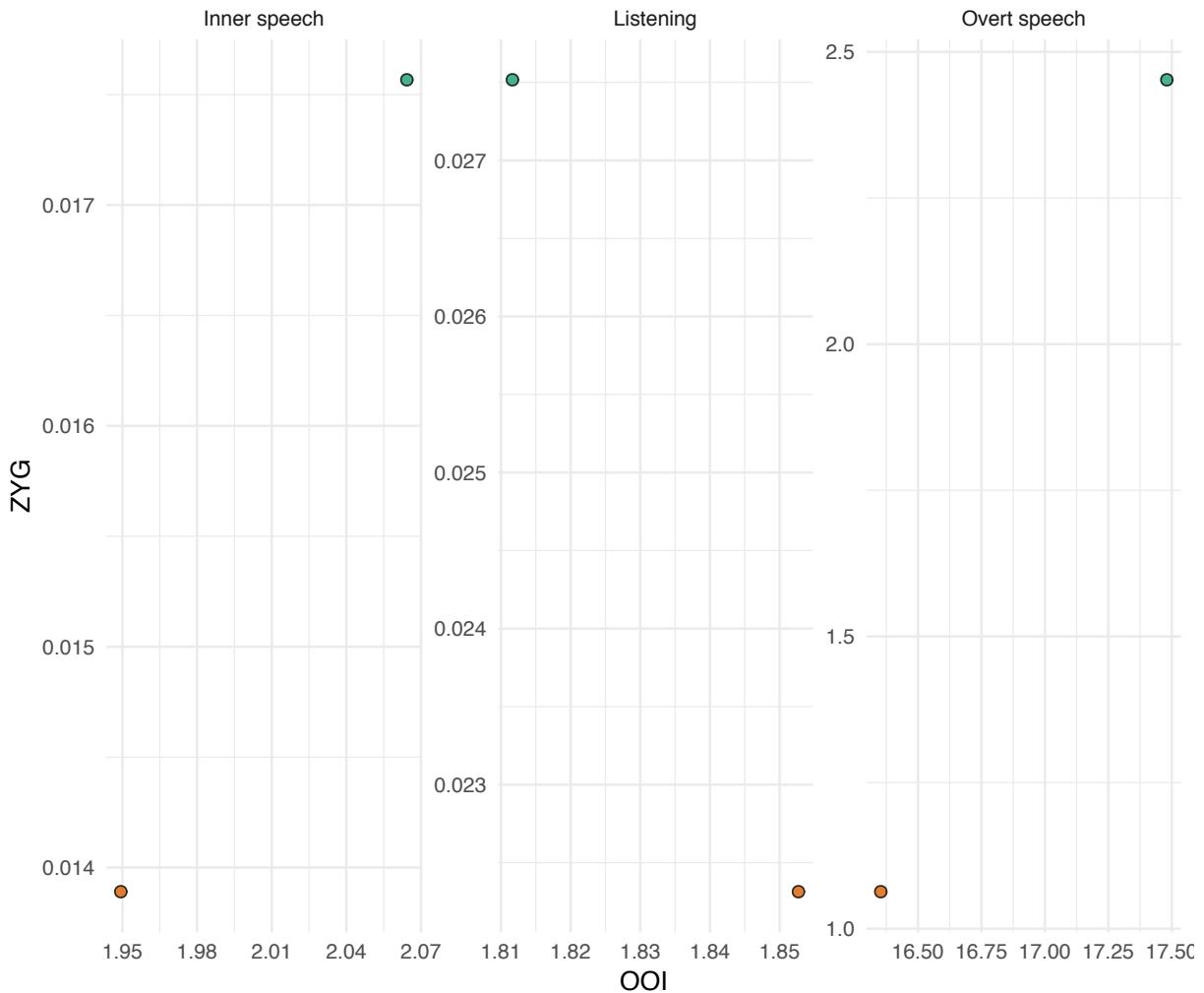


Figure 5.6: Average EMG activity for each nonword in each condition, in the 2D space formed by the OOI and the ZYG.

In other words, it is easier to discriminate these signals in the multidimensional space of all speech muscles, rather than by considering each muscle independently. Thus, we used a supervised machine learning algorithm aiming to classify speech signals according to the class of nonwords. Broadly, the machine learning approach seeks to find a relationship between an input X (e.g., EMG recordings over the four facial muscles) and an output Y (e.g., the class of nonwords). Once trained, it allows predicting a value of the output based on some input values, whose prediction can be evaluated against new observations.

We used a random forest algorithm, as implemented in the caret package (Jed Wing et al., 2018). Random forests (RFs) represent an ensemble of many decision trees (a forest),

which allow predictions to be made based on a series of decision rules (e.g., is the score on predictor x_1 higher or lower than z ? If yes, then ..., if not, then ...). The specificity of RFs is to combine a large number of trees (usually above 100 trees), and to base the final conclusion on the average of these trees, thus preventing overfitting. We used three separate RFs to classify EMG signals in each condition (Overt Speech, Inner Speech, and Listening).

To evaluate the performance of this approach, we report the raw accuracy (along with its resampling-based 95% confidence interval), or the proportion of data points in the test dataset for which the RF algorithm predicted the correct class of nonwords. First, we randomly split the entire dataset into a training (80%) and a test set (20%). The training set was used for the learning while the test set was used to evaluate the predictions of the algorithm. To prevent overfitting, we used repeated 10-fold cross-validation during the learning phase.

5.6.2.1 Predicting the class of nonwords during overt speech production

We first tried to predict the class of nonwords produced in overt speech, based on the activity of the four facial muscles (OOI, ZYG, COR, FRO). Each predictor was centred to its mean and standardised before the analysis.

Table 5.4: Confusion matrix with by-class error for the overt speech condition.

		Reference		
Prediction		rounded	spread	class.error
rounded		971	165	0.145
spread		204	956	0.176

This analysis revealed an overall classification accuracy of 0.841, 95% CI [0.809, 0.87]. The relative importance of each feature (i.e., each muscle) for prediction is represented in Figure 5.7.

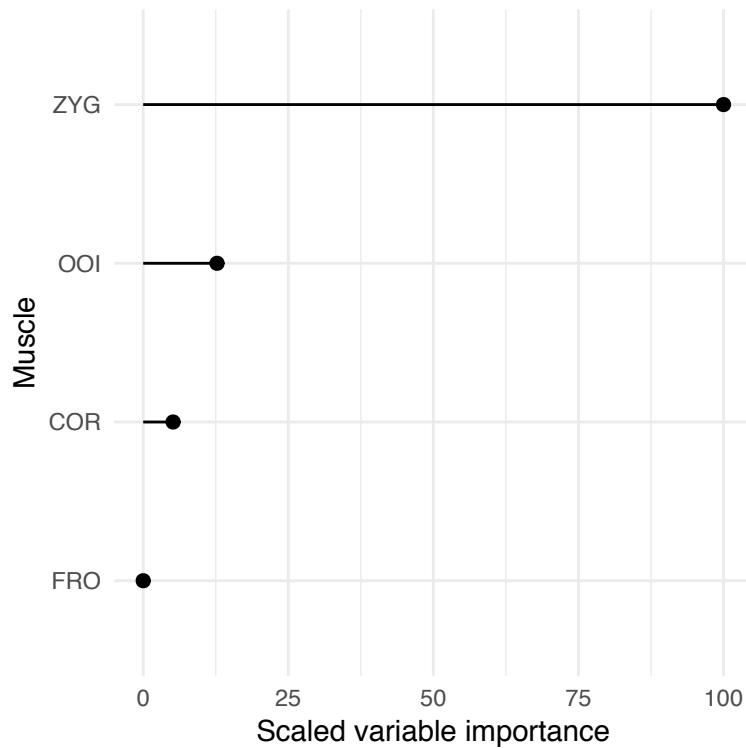


Figure 5.7: Scaled variable importance for overt speech classification.

This figure reveals that the muscles containing most information to discriminate the two classes of nonwords are the ZYG and the OOI, whereas, as predicted, forehead muscles do not seem to strongly contribute to predictive accuracy during overt speech production.

5.6.2.2 Predicting the class of nonwords during inner speech production and listening

We then applied the same strategy (the same algorithm) to the signals recorded in the inner speech and listening conditions. The results of these analyses are reported in Table 5.5 and Table 5.6.

Table 5.5: Confusion matrix with by-class classification error for the inner speech condition.

		Reference		
		rounded	spread	class.error
Prediction	rounded	460	550	0.545
	spread	517	532	0.493

This analysis revealed an overall classification accuracy of 0.508, 95% CI [0.464, 0.552] in the inner speech condition, which indicates that the RF algorithm did not allow discriminating the two classes of nonwords better than random guessing.

Table 5.6: Confusion matrix with by-class classification error for the listening condition.

Prediction	Reference		
	rounded	spread	class.error
rounded	512	517	0.502
spread	525	490	0.517

This analysis similarly revealed an overall classification accuracy of 0.488, 95% CI [0.444, 0.533] in the listening condition.

5.7 Discussion

With this study we aimed to replicate and extend previous findings showing that facial electromyography can be used to discriminate inner speech content (e.g., McGuigan & Dollins, 1989; McGuigan & Winstead, 1974). As these studies used small samples of children, our study aimed to examine whether such results can be reproduced using surface electromyography and modern signal processing methods in an adult sample.

To this end, it was crucial to first show that the EMG correlates of our two classes of nonwords were discriminable during overt speech production. Surprisingly, the data we collected during overt speech production do not corroborate the hypothesis according to which the average EMG amplitude of the OOI should be higher during the production of “rounded” nonwords as compared to “spread” nonwords. For both orofacial speech muscles (OOI and ZYG), the average EMG amplitude was higher for rounded nonwords than for spread nonwords during overt speech production. Moreover, while the average EMG amplitude recorded over speech muscles was higher than baseline in both the inner speech and listening conditions, we did not find differences of activation according to the content of the material (the class of nonword). An automatic classification approach, using the four facial muscles, revealed that although it was possible to discriminate EMG signals related to the two classes of nonwords with a reasonable accuracy during overt speech production, this approach failed in discriminating these two classes during inner speech production or during listening. We also observed a higher EMG amplitude recorded over the facial (both orofacial and non-orofacial) muscles during inner speech production and during the listening of speech production than during rest. However, as pinpointed by Garrity (1977), this observation is not sufficient to conclude that these activations were actually related to inner speech production, because i) both orofacial speech-related muscles and forehead non-speech related muscles showed similar EMG amplitude changes from baseline and ii) we did not observe different changes in EMG amplitude depending on the content of inner speech (i.e., depending on the class of nonword to be uttered).

Before discussing the theoretical implications of these results, two main issues are worth discussing. First, how can we explain that rounded nonwords were associated with higher EMG amplitude during overt speech on both OOI and ZYG muscles? Second, how can we explain the indiscriminability of inner speech content, which seems to contradict classic as well as recent findings in the field (e.g., Kapur et al., 2018)? We turn to each of these questions in the following.

To answer the first question, we began by comparing our results to results obtained by another group (Eskes et al., 2017). The authors of this study recorded surface EMG activity from five participants while they were producing seven facial expressions and five isolated vowel sounds (/a/, /e/, /i/, /o/, /u/). They recorded EMG activity over eight facial muscles (the zygomaticus major (ZYG), the risorius (RIS), the orbicularis oris superior (OOS) and inferior (OOI), the mentalis (MEN), the depressor anguli oris (DAO), the levator labii superioris (LLS) muscles, and the digastric muscle (DIG)). We divided these vowels in two classes to fit our own classes of nonwords. More precisely, we have created the following two classes: a *rounded* class, composed of the vowels /o/ and /u/, and a *spread* class, composed of the vowels /e/ and /i/¹⁰. We present the average EMG amplitude recorded over the OOI and the ZYG according to the vowel class in Table 5.7.

Table 5.7: Standardised EMG amplitude recorded over the OOI and the ZYG during overt speech production of rounded versus spread vowels in Eskes et al. (2017).

Muscle	Item	Observations	Mean	SD	Median	Histogram
OOI	rounded	50	59.7	60.09	42.03	
OOI	spread	50	22.15	11.92	20.65	
ZYG	rounded	50	7.39	3.78	6.27	
ZYG	spread	50	10.15	6.2	7.99	

Note. The number of observations is given by the number of vowels to be pronounced in each category (2) times the number of repetitions (5) times the number of participants (5), for a total of 50 observations per cell.

We notice that Eskes et al. (2017) have indeed observed the dissociation we initially predicted, that is, that the EMG amplitude recorded over the OOI was higher during the pronunciation of rounded vowels than during pronunciation of spread vowels, while the reverse pattern was observed concerning the ZYG¹¹. However, one crucial difference between Eskes et al. (2017) design and ours is the complexity of the linguistic material. Whereas Eskes et al. (2017) used single phonemes, we chose to use bisyllabic nonwords to increase the ecological validity of the paradigm. Although these nonwords were specifically created to theoretically increase the engagement of either the OOI or the ZYG (see section 5.5.2.2), it is reasonable to expect differences in the average EMG amplitude between the phoneme and the (non)word level. More precisely, we expect the *average* EMG amplitude associated with the production of a given phoneme (e.g., /y/) to be impacted by the production of the consonant (e.g., /b/) it is paired with, due to coarticulation. More generally, we could hypothesise that the difference between the *average* EMG amplitude recorded during the production of the phoneme /i/ and during the production of the phoneme /y/ could be reduced when these phonemes are coarticulated in CV or CVCV sequences like /byby/ or /didi/. In other words, we might expect an interaction effect

¹⁰We did not include the vowel /a/ because it theoretically does not fit in one of these two categories.

¹¹Paired-samples Wilcoxon signed rank tests revealed a significant shift in location (pseudomedian) between rounded and spread items for the OOI ($\beta = 24.12$, 95% CI [15.19, 40.77], $V = 1184$, $p < .001$) with rounded items being associated with a higher location than spread items. This analysis revealed a significant shift in the inverse direction concerning the ZYG ($\beta = -1.51$, 95% CI [-2.94, -0.48], $V = 275$, $p < .001$).

between the structure of the to-be produced speech sequence (either a single vowel or a CV/CVCV sequence) and the class of the vowel. This is coherent with previous findings showing that the muscular activity associated with vowels production is strongly influenced by the surrounding consonants in CVC sequences (e.g., Fromkin, 1966). Thus, further investigations should focus on how the average EMG amplitude is impacted by coarticulation during the production of CVCV sequences.

With regards to inner speech, our results do not support theoretical predictions of the *motor simulation view*, according to which it should be possible to discriminate classes of nonwords produced in inner speech based on EMG signals. Whereas this outcome is consistent with some recent results (Meltzner et al., 2008)¹², it also stands in sharp contrast with classical results in the field (e.g., McGuigan & Dollins, 1989; McGuigan & Winstead, 1974) 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. There are a few crucial differences between Kapur et al. (2018)'s work and ours that stand as good candidates to explain the discrepancies between our results. First, the strategy adopted to position the sensors was radically different. Following guidelines from the field of psychophysiology, our strategy was to position sensors precisely over the facial muscles of interest, aligned with the direction of the muscle fibers and in theoretically optimal positions to record activity of this muscle while reducing cross-talk. However, precisely because of pervasive cross-talk in facial surface EMG recordings, this strategy, whereas maximising the probability of recording activity from a given single muscle, was also (as a result) reducing the probability of recording activity from potentially speech-relevant neighbour muscles. Therefore, this strategy might work sub-optimally when the goal of the experiment is to extract the maximum amount of (relevant) EMG information to discriminate inner speech content. However, this problem might be mitigated by using more sensors and a more lenient sensor-positioning approach. Whereas we recorded the EMG amplitude over only two lower facial muscles (OOI and ZIG), Kapur et al. (2018) analysed EMG data from seven different sensors, whose position and number was defined iteratively in order to maximise the classification accuracy. In other words, the parameters of the experiment were iteratively optimised to maximise a certain outcome (classification accuracy). This strategy is radically different from the classical approach in experimental and cognitive psychology where experimental conditions are defined to test theoretically derived hypotheses. Whereas the first approach is arguably more efficient at solving a particular problem at hand, the second approach might be more efficient in tackling theoretical questions. For instance, a recent study reported a greater EMG amplitude of laryngeal and lip muscles during auditory verbal tasks (covert singing) than during visual imagery tasks (Pruitt, Halpern, & Pfodrescher, 2018). By coupling EMG recording with demographic and psychological measures, they were able to show that these correlates were related to the level of accuracy in singing, thus shedding light upon the nature and functions of peripheral muscular activity during covert singing.

Putting aside considerations related to methodological aspects of the present study, these results do not corroborate the *motor simulation view* of inner speech production.

¹²The authors of this study 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, words were only repeated three times, which might have lead to poor sensitivity. Interestingly and despite the lack of peripheral muscular activation during covert speech, they have observed similar respiratory activity between overt and covert speech, echoing previous findings (e.g., Conrad & Schönle, 1979).

Instead, it seems to support the *abstraction view*, which postulates that inner speech results from the activation of abstract linguistic representations. However, individual differences in discriminability highlight that the abstractness of inner speech might be flexible (???). Indeed, although for most participants it was not possible to discriminate the content of inner speech, it was possible to discriminate the content of inner speech for two of them (S_15 and S_17). This suggests either that the extent to which inner speech production recruits the speech motor system might vary between individuals or that it might vary within individual depending on the properties of the ongoing task (these two suggestions are not mutually exclusive). For instance, we know from early research on the EMG correlates of inner speech that the average amplitude of these correlates tend to be higher when the task is more difficult (i.e., requires more effort, Sokolov, 1972). As such, the extent to which inner speech production recruits the speech motor system could be moderated by manipulating the difficulty of the ongoing task. In addition, we know that the electromyographic activity recorded during motor imagery could be moderated by the perspective taken in motor imagery. A distinction is made between first-person perspective or *internal imagery* (i.e., imagining an action as we would execute it) and third-person perspective or *external imagery* (i.e., imagining an action as an observer of this action), that seem to involve different neural and cognitive processes. It has been shown that a first-person perspective generally results in greater EMG activity than motor imagery in a third-person perspective (Hale, 1982; Harris & Robinson, 1986). Moreover, the first-person perspective tends to be associated with more kinaesthetic feelings than the third-person one (which relies more heavily on visual percepts). While the perspective issue does not apply to inner speech production, we hypothesise that involvement of the speech motor system during inner speech production may be moderated by the specific instructions given to the participants. For instance, by instructing participants to focus on *inner speaking* (imagining speaking), instead of *inner hearing* (imagining hearing), and by asking them to focus on the kinaesthetic feelings related to speech acts (rather than on auditory percepts), we would expect to find a higher average EMG amplitude recorded over the speech muscles.

Of course, the current study and the above discussion should be interpreted with a few words of caution in mind. Although the number of observations reported in the present study is reasonable¹³, the sensibility of the experiment could be improved by increasing the number of observations and/or by reducing two important sources of variation. More precisely, one could reduce the variance related to the item (the specific nonword being uttered) by selecting nonwords that are more similar to each other in the way they are uttered, by selecting less items or simpler items. Similarly, particular attention should be devoted to reducing inter-participant variability, which could be done by using more guided and specific instructions, as well as a longer training phase to familiarise the participant with the task.

In summary, we have demonstrated that while surface electromyography may lead to reasonable accuracy in discriminating classes of nonwords during overt speech production (using signals recorded over only two speech-related muscles), it did not permit to discriminate these two classes during inner speech production. These results, in comparison with results obtained by other teams (e.g., Kapur et al., 2018), highlight that depending on the aim of the research, different strategies might be more or less successfully

¹³For each class of nonwords, we collected around $6 \times 10 = 60$ observations by condition and by participant. For 26 participants and two classes of nonwords, this results in 26 (participants) \times 120 (individual trials) \times 3 (conditions) = 9360 observations. However, after rejecting trials with movement artefacts, we had 7997 observations in total.

pursued. More precisely, if the goal is to attain high classification accuracy (problem-solving approach), then the parameters of the experiment (e.g., number of repetitions, number of sensors, position of the sensors, parameters of the signal processing workflow) should be optimised based on the desired outcome (i.e., classification accuracy). However, the classical laboratory strategy used in experimental and cognitive psychology, aiming to compare specific conditions (or muscles) to each other in a controlled environment, is deemed to be more appropriate when the aim of the research is to sharpen our understanding of the psychological phenomenon under study.

5.8 Supplementary materials

Pre-registered protocol, open data, as well as reproducible code and figures are available at <https://osf.io/czer4>.

Aside from previously cited packages, several other packages have been used for the writing of this paper, among which the `ggrepel` and `ggplot2` packages for plotting (Slowikowski, 2018; Wickham et al., 2018) as well as the `tidyverse`, `sjstats`, `here`, `skimr`, and `glue` packages for code writing and formatting (Hester, 2017; Lüdecke, 2018; McNamara, Arino de la Rubia, Zhu, Ellis, & Quinn, 2018; Müller, 2017; Wickham, 2017).

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Summary of Chapter 5

Blah blah ...

ARTICULATORY SUPPRESSION EFFECTS ON INDUCED RUMINATION

Summary of the research...¹

Summary of Chapter 6

Blah blah ...

¹This experimental chapter is a submitted manuscript reformatted for the need of this thesis. Pre-registered protocol, preprint, data, as well as reproducible code and figures are available at: <https://osf.io/3bh67/>.

REFINING THE INVOLVEMENT OF THE SPEECH MOTOR SYSTEM DURING RUMINATION: A DUAL-TASK INVESTIGATION

Summary of the research...¹

Summary of Chapter 7

Blah blah ...

¹This experimental chapter is a submitted manuscript reformatted for the need of this thesis. Pre-registered protocol, preprint, data, as well as reproducible code and figures are available at: <https://osf.io/8ab2d/>.

Part III

Discussion and conclusions

DISCUSSION AND PERSPECTIVES

8.1 Summary of the results

...

8.2 Benchmarks for theories of inner speech

A revised version of MacKay (1992) constraints...

8.3 Limitations and ways forward

...

8.4 Conclusions

...

REFERENCES

- Abramson, M., & Goldinger, S. D. (1997). What the reader's eye tells the mind's ear: Silent reading activates inner speech. *Perception & Psychophysics*, 59(7), 1059–1068. <https://doi.org/10.3758/BF03205520>
- Alderson-Day, B., & Fernyhough, C. (2015). Inner speech: Development, cognitive functions, phenomenology, and neurobiology. *Psychological Bulletin*, 141(5), 931–965. <https://doi.org/10.1037/bul0000021>
- 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>
- Anderson, R. E. (1982). Speech imagery is not always faster than visual imagery. *Memory & Cognition*, 10(4), 371–380. <https://doi.org/10.3758/BF03202429>
- Aust, F., & Barth, M. (2018). *Papaja: Prepare reproducible apa journal articles with r markdown*. Retrieved from <https://github.com/crsh/papaja>
- Babault, N., Pousson, M., Michaut, A., & Van Hoecke, J. (2003). Effect of quadriceps femoris muscle length on neural activation during isometric and concentric contractions. *Journal of Applied Physiology*, 94(3), 983–990. <https://doi.org/10.1152/japplphysiol.00717.2002>
- Baddeley, A. (1986). *Working memory*. New York, NY, US: Clarendon Press/Oxford University Press.
- Baddeley, A. D., & Wilson, B. (1985). Phonological coding and short-term memory in patients without speech. *Journal of Memory and Language*, 24(4), 490–502. [https://doi.org/10.1016/0749-596X\(85\)90041-5](https://doi.org/10.1016/0749-596X(85)90041-5)
- Bakan, D. (1966). The test of significance in psychological research. *Psychological Bulletin*, 66(6), 423–437. <https://doi.org/10.1037/h0020412>
- Barlow, S. M., & Netsell, R. (1986). Differential Fine Force Control of the Upper and Lower Lips. *Journal of Speech, Language, and Hearing Research*, 29(2), 163–169. <https://doi.org/10.1044/jshr.2902.163>
- Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, 59, 617–645. <https://doi.org/10.1146/annurev.psych.59.113007.100000>

//doi.org/10.1146/annurev.psych.59.103006.093639

Basho, S., Palmer, E. D., Rubio, M. A., Wulfeck, B., & Müller, R.-A. (2007). Effects of generation mode in fMRI adaptations of semantic fluency: Paced production and overt speech. *Neuropsychologia*, 45(8), 1697–1706. <https://doi.org/10.1016/j.neuropsychologia.2007.01.007>

Bååth, R. (2018). *BayesianFirstAid: Bayesian replacements for the most commonly used statistical tests in r*. Retrieved from <http://www.sumsar.net>

Binet, A. (1886). *La psychologie du raisonnement. Recherches expérimentales par l'hypnotisme*. Alcan, Paris.

Bonnet, M., Decety, J., Jeannerod, M., & Requin, J. (1997). Mental simulation of an action modulates the excitability of spinal reflex pathways in man. *Cognitive Brain Research*, 5(3), 221–228. [https://doi.org/10.1016/S0926-6410\(96\)00072-9](https://doi.org/10.1016/S0926-6410(96)00072-9)

Boxtel, A. (2001). Optimal signal bandwidth for the recording of surface EMG activity of facial, jaw, oral, and neck muscles. *Psychophysiology*, 38(1), 22–34. <https://doi.org/10.1111/1469-8986.3810022>

Boxtel, A. van, & 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>

Boyd, E. M., & Fales, A. W. (1983). Reflective Learning: Key to Learning from Experience. *Journal of Humanistic Psychology*, 23(2), 99–117. <https://doi.org/10.1177/0022167883232011>

Brewer, W. F. (1986). What is autobiographical memory? In D. C. Rubin (Ed.), *Autobiographical Memory* (pp. 25–49). Cambridge: Cambridge University Press. <https://doi.org/10.1017/CBO9780511558313.006>

Brisinda, D., Venuti, A., Sorbo, A. R., Cataldi, C., Iantorno, E., & Fenici, R. (2013). Comparison between standard short-term, very-short and ultra-short-term heart rate variability analysis in healthy subjects during exercise testing. *European Heart Journal*, 34(suppl_1). <https://doi.org/10.1093/eurheartj/eht309.P3384>

Brosschot, J. F., Gerin, W., & Thayer, J. F. (2006). The perseverative cognition hypothesis: A review of worry, prolonged stress-related physiological activation, and health. *Journal of Psychosomatic Research*, 60(2), 113–124. <https://doi.org/10.1016/j.jpsychores.2005.06.074>

Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach* (2nd ed). New York: Springer.

Burnham, K. P., & Anderson, D. R. (2004). Multimodel Inference: Understanding AIC and BIC in Model Selection. *Sociological Methods & Research*, 33(2), 261–304. <https://doi.org/10.1177/0049124104268644>

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

Carpenter, B., Gelman, A., Hoffman, M., Lee, D., Goodrich, B., Betancourt, M., ... 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>
- Cefidekhanie, A. H., Savariaux, C., Sato, M., & Schwartz, J.-l. (2014). Interaction between articulatory gestures and inner speech in a counting task. *Journal of the Acoustical Society of America*, 136(4), 1869–1879. <https://doi.org/10.1121/1.4893910>
- Chang, W., Cheng, J., Allaire, J., Xie, Y., & McPherson, J. (2018). *Shiny: Web application framework for r*. Retrieved from <https://CRAN.R-project.org/package=shiny>
- Christoff, K., Irving, Z. C., Fox, K. C. R., Spreng, R. N., & Andrews-Hanna, J. R. (2016). Mind-wandering as spontaneous thought: A dynamic framework. *Nature Reviews Neuroscience*, 17(11), 718–731. <https://doi.org/10.1038/nrn.2016.113>
- Cohen, B. H. (1986). The motor theory of voluntary thinking. In R. J. Davidson, G. E. Schatz, & D. Shapiro (Eds.), *Consciousness and self-regulation*. Springer, Boston, MA.
- Coltheart, V. (1999). Phonological codes in reading comprehension, short-term memory, and memory for rapid visual sequences. In *Fleeting memories: Cognition of brief visual stimuli* (pp. 181–223). Cambridge, MA, US: The MIT Press.
- Conrad, A., & Roth, W. T. (2007). Muscle relaxation therapy for anxiety disorders: It works but how? *Journal of Anxiety Disorders*, 21(3), 243–264. <https://doi.org/10.1016/j.janxdis.2006.08.001>
- Conrad, B., & Schönle, P. (1979). Speech and respiration. *Archiv Für Psychiatrie Und Nervenkrankheiten*, 226(4), 251–268. <https://doi.org/10.1007/BF00342238>
- Conway, M. A. (1990). *Autobiographical memory: An introduction*. Open University Press.
- Conway, M., Csank, P. A. R., Holm, S. L., & Blake, C. K. (2000). On Assessing Individual Differences in Rumination on Sadness. *Journal of Personality Assessment*, 75(3), 404–425. https://doi.org/10.1207/S15327752JPA7503_04
- Corley, M., Brocklehurst, P. H., & Moat, H. S. (2011). Error biases in inner and overt speech: Evidence from tongue twisters. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37(1), 162–175. <https://doi.org/10.1037/a0021321>
- Cumming, G. (2012). *Understanding the new statistics: Effect sizes, confidence intervals, and meta-analysis*. (New York:).
- Cumming, G. (2014). The New Statistics: Why and How. *Psychological Science*, 25(1), 7–29. <https://doi.org/10.1177/0956797613504966>
- Decety, J., & Jeannerod, M. (1996). Mentally simulated movements in virtual reality: Does Fitts's law hold in motor imagery? *Behavioural Brain Research*, 8.
- Decety, J., Jeannerod, M., & Prablanc, C. (1989). The timing of mentally represented actions. *Behavioural Brain Research*, 34(1-2), 35–42.
- Dell, G. S., & Repka, R. J. (1992). Errors in Inner Speech. In B. J. Baars (Ed.), *Experimental Slips and Human Error: Exploring the Architecture of Volition* (pp. 237–262). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4899-1164-3_10
- De Luca, C. J. (1997). The Use of Surface Electromyography in Biomechanics. *Journal of Applied Biomechanics*, 13(2), 135–163. <https://doi.org/10.1123/jab.13.2.135>

- 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.biomech.2010.01.027>
- De Raedt, R., Hertel, P. T., & Watkins, E. R. (2015). Mechanisms of Repetitive Thinking: Introduction to the Special Series. *Clinical Psychological Science*, 3(4), 568–573. <https://doi.org/10.1177/2167702615584309>
- Douilliez, C., Philippot, P., Heeren, A., Watkins, E. R., & Barnard, P. (2012). The Mini-CERTS (Cambridge-Exeter Repetitive Thought Scale): A Short Questionnaire to Assess Constructive and Unconstructive Repetitive Thinking. *Revue Canadienne Des Sciences Du Comportement/Canadian Journal of Behavioural Science.*, 1–19.
- Ehrich, J. (2006). Vygotskian Inner Speech. *Australian Journal of Educational & Developmental Psychology*, 6, 12–25.
- 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>
- Ekman, P., & Friesen, W. (1978). *Facial coding action system (FACS): A technique for the measurement of facial actions*. Palo Alto, CA: Consulting Psychologists Press.
- Eske, M., Alphen, M. J. A. van, Balm, A. J. M., Smeele, L. E., Brandsma, D., & Heijden, F. van der. (2017). Predicting 3D lip shapes using facial surface EMG. *PLOS ONE*, 12(4), e0175025. <https://doi.org/10.1371/journal.pone.0175025>
- Everdell, I. T., Marsh, H., Yurick, M. D., Munhall, K. G., & Paré, M. (2007). Gaze Behaviour in Audiovisual Speech Perception: Asymmetrical Distribution of Face-Directed Fixations. *Perception*, 36(10), 1535–1545. <https://doi.org/10.1068/p5852>
- Fadiga, L., Buccino, G., Craighero, L., Fogassi, L., Gallese, V., & Pavesi, G. (1999). Corticospinal excitability is specifically modulated by motor imagery a magnetic stimulation study. *Neuropsychologia*, 37(2), 147–158. [https://doi.org/10.1016/s0028-3932\(98\)00089-x](https://doi.org/10.1016/s0028-3932(98)00089-x)
- Feinberg, I. (1978). Efference Copy and Corollary Discharge: Implications for Thinking and Its Disorders. *Schizophrenia Bulletin*, 4(4), 636–640. <https://doi.org/10.1093/schbul/4.4.636>
- Findley, D. F. (1985). On the unbiasedness property of AIC for exact or approximating linear stochastic time series models. *Journal of Time Series Analysis*, 6(4), 229–252. <https://doi.org/10.1111/j.1467-9892.1985.tb00412.x>
- Flavell, J. H., Beach, D. R., & Chinsky, J. M. (1966). Spontaneous Verbal Rehearsal in a Memory Task as a Function of Age. *Child Development*, 37(2), 283. <https://doi.org/10.2307/1126804>
- Fridlund, A. J., & Cacioppo, J. T. (1986). Guidelines for Human Electromyographic Research. *Psychophysiology*, 23(5), 567–589. <https://doi.org/10.1111/j.1469-8986.1986.tb00676.x>
- Fromkin, V. A. (1966). Neuro-Muscular Specification of Linguistic Units. *Language and Speech*, 9(3), 170–199. <https://doi.org/10.1177/002383096600900304>
- Fuhrer, R., & Rouillon, F. (1989). La version française de l'échelle CES-D (Center for

- Epidemiologic Studies-Depression Scale). Description et traduction de l'échelle d'autoévaluation. *Psychiatrie & Psychobiologie*, 4(3), 163–166.
- Gabry, J., Simpson, D., Vehtari, A., Betancourt, M., & Gelman, A. (2019). Visualization in Bayesian workow. *Journal of the Royal Statistical Society: Series A (Statistics in Society)*, 182(2), 389–402. <https://doi.org/10.1111/rss.a.12378>
- 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>
- Garrity, L. I. (1977). Electromyography: A review of the current status of subvocal speech research. *Memory & Cognition*, 5(6), 615–622. <https://doi.org/10.3758/BF03197407>
- 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.
- Gelman, A., & Hill, J. (2006). *Data Analysis Using Regression and Multilevel/Hierarchical Models*. Leiden: Cambridge University Press.
- Gentsch, A., Weber, A., Synofzik, M., Vosgerau, G., & Schütz-Bosbach, S. (2016). Towards a common framework of grounded action cognition: Relating motor control, perception and cognition. *Cognition*, 146, 81–89. <https://doi.org/10.1016/j.cognition.2015.09.010>
- Geva, S., Bennett, S., Warburton, E. A., & Patterson, K. (2011). Discrepancy between inner and overt speech: Implications for post-stroke aphasia and normal language processing. *Aphasiology*, 25(3), 323–343. <https://doi.org/10.1080/02687038.2010.511236>
- Gigerenzer, G. (2004). Mindless statistics. *Journal of Socio-Economics*, 33(5), 587–606. <https://doi.org/10.1016/j.socec.2004.09.033>
- Glover, S., & Baran, M. (2017). The motor-cognitive model of motor imagery: Evidence from timing errors in simulated reaching and grasping. *Journal of Experimental Psychology: Human Perception and Performance*, 43(7), 1359–1375. <https://doi.org/10.1037/xhp0000389>
- 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>
- Grush, R. (2004). The emulation theory of representation: Motor control, imagery, and perception. *Behavioral and Brain Sciences*, 27(03). <https://doi.org/10.1017/S0140525X04000093>
- Grzes, J., & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation, and verb generation of actions: A meta-analysis. *Human Brain Mapping*, 12(1), 1–19. [https://doi.org/10.1002/1097-0193\(200101\)12:1%3C1::AID-HBM10%3E3.0.CO;2-V](https://doi.org/10.1002/1097-0193(200101)12:1%3C1::AID-HBM10%3E3.0.CO;2-V)

- Guerrero, J. A., & Macias-Diaz, J. E. (2018). *BiosignalEMG: Tools for electromyogram signals (emg) analysis*. Retrieved from <https://CRAN.R-project.org/package=biosignalEMG>
- Guillot, A., & Collet, C. (2005). Contribution from neurophysiological and psychological methods to the study of motor imagery. *Brain Research Reviews*, 50(2), 387–397. <https://doi.org/10.1016/j.brainresrev.2005.09.004>
- Guillot, A., Collet, C., Nguyen, V. A., Malouin, F., Richards, C., & Doyon, J. (2009). Brain activity during visual versus kinesthetic imagery: An fMRI study. *Human Brain Mapping*, 30(7), 2157–2172. <https://doi.org/10.1002/hbm.20658>
- Guillot, A., Di Rienzo, F., MacIntyre, T., Moran, A., & Collet, C. (2012). Imagining is Not Doing but Involves Specific Motor Commands: A Review of Experimental Data Related to Motor Inhibition. *Frontiers in Human Neuroscience*, 6. <https://doi.org/10.3389/fnhum.2012.00247>
- Guillot, A., Lebon, F., & Collet, C. (2010). Electromyographic activity during motor imagery. In A. Guillot & C. Collet (Eds.), *The neurophysiological foundations of mental and motor imagery* (pp. 83–94). Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780199546251.003.0006>
- Hackmann, A., & Holmes, E. A. (2004). Reflecting on imagery: A clinical perspective and overview of the special issue of *memory* on mental imagery and memory in psychopathology. *Memory*, 12(4), 389–402. <https://doi.org/10.1080/09658210444000133>
- Haggard, P. (2005). Conscious intention and motor cognition. *Trends in Cognitive Sciences*, 9(6), 290–295. <https://doi.org/10.1016/j.tics.2005.04.012>
- Hale, B. D. (1982). The Effects of Internal and External Imagery on Muscular and Ocular Concomitants. *Journal of Sport Psychology*, 4(4), 379–387. <https://doi.org/10.1123/jsp.4.4.379>
- Harris, D. V., & Robinson, W. J. (1986). The Effects of Skill Level on EMG Activity during Internal and External Imagery. *Journal of Sport Psychology*, 8(2), 105–111. <https://doi.org/10.1123/jsp.8.2.105>
- Heavey, C. L., & Hurlburt, R. T. (2008). The phenomena of inner experience. *Consciousness and Cognition*, 17(3), 798–810. <https://doi.org/10.1016/j.concog.2007.12.006>
- Hester, J. (2017). *Glue: Interpreted string literals*. Retrieved from <https://CRAN.R-project.org/package=glue>
- Hétu, S., Grégoire, M., Saimpont, A., Coll, M.-P., Eugène, F., Michon, P.-E., & Jackson, P. L. (2013). The neural network of motor imagery: An ALE meta-analysis. *Neuroscience & Biobehavioral Reviews*, 37(5), 930–949. <https://doi.org/10.1016/j.neubiorev.2013.03.017>
- Holmes, E. A., & Mathews, A. (2005). Mental Imagery and Emotion: A Special Relationship? *Emotion*, 5(4), 489–497. <https://doi.org/10.1037/1528-3542.5.4.489>
- 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>
- Houde, J. F., & Nagarajan, S. S. (2011). Speech Production as State Feedback Control.

- Frontiers in Human Neuroscience*, 5. <https://doi.org/10.3389/fnhum.2011.00082>
- Huey, E. B. (1968). *The Psychology and Pedagogy of Reading*. Cambridge, MA: MIT Press. Retrieved from <https://mitpress.mit.edu/books/psychology-and-pedagogy-reading>
- Huffziger, S., Ebner-Priemer, U., Koudela, S., Reinhard, I., & Kuehner, C. (2012). Induced rumination in everyday life: Advancing research approaches to study rumination. *Personality and Individual Differences*, 53(6), 790–795. <https://doi.org/10.1016/j.paid.2012.06.009>
- 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.
- Jäncke, L. (1996). Facial EMG in an anger-provoking situation: Individual differences in directing anger outwards or inwards. *International Journal of Psychophysiology*, 23(3), 207–214. [https://doi.org/10.1016/S0167-8760\(96\)00062-1](https://doi.org/10.1016/S0167-8760(96)00062-1)
- Jäncke, L., Vogt, J., Musial, F., Lutz, K., & Kalveram, K. T. (1996). Facial EMG responses to auditory stimuli. *International Journal of Psychophysiology*, 22(1-2), 85–96. [https://doi.org/10.1016/0167-8760\(96\)00013-X](https://doi.org/10.1016/0167-8760(96)00013-X)
- Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery. *Behavioral and Brain Sciences*, 17(02), 187. <https://doi.org/10.1017/S0140525X00034026>
- Jeannerod, M. (1995). Mental imagery in the motor context. *Neuropsychologia*, 33(11), 1419–1432. [https://doi.org/10.1016/0028-3932\(95\)00073-C](https://doi.org/10.1016/0028-3932(95)00073-C)
- Jeannerod, M. (1999). The 25th Bartlett Lecture: To Act or Not to Act: Perspectives on the Representation of Actions. *The Quarterly Journal of Experimental Psychology Section A*, 52(1), 1–29. <https://doi.org/10.1080/713755803>
- Jeannerod, M. (2001). Neural Simulation of Action: A Unifying Mechanism for Motor Cognition. *NeuroImage*, 14(1), S103–S109. <https://doi.org/10.1006/nimg.2001.0832>
- Jeannerod, M. (2006). *Motor cognition: What actions tell the self*. Oxford ; New York: Oxford University Press.
- Jed Wing, M. K. C. from, Weston, S., Williams, A., Keefer, C., Engelhardt, A., Cooper, T., ... Hunt., T. (2018). *Caret: Classification and regression training*. Retrieved from <https://CRAN.R-project.org/package=caret>
- 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>
- Jones, S. R., & Fernyhough, C. (2007). Thought as action: Inner speech, self-monitoring, and auditory verbal hallucinations. *Consciousness and Cognition*, 16(2), 391–399. <https://doi.org/10.1016/j.concog.2005.12.003>
- Jordan, M. I., & Rumelhart, D. E. (1992). Forward Models: Supervised Learning with a Distal Teacher. *Cognitive Science*, 16(3), 307–354. https://doi.org/10.1207/s15516709cog1603_1
- Judd, C. M., McClelland, G. H., & Ryan, C. S. (2009). *Data analysis: A model comparison*

- approach, 2nd ed.* New York, NY, US: Routledge/Taylor & Francis Group.
- Kamen, G., & Gabriel, D. A. (2010). *Essentials of electromyography*. Champaign, IL: Human Kinetics.
- Kapur, A., Kapur, S., & Maes, P. (2018). AlterEgo: A Personalized Wearable Silent Speech Interface. In *Proceedings of the 2018 Conference on Human Information Interaction&Retrieval - IUI '18* (pp. 43–53). Tokyo, Japan: ACM Press. <https://doi.org/10.1145/3172944.3172977>
- Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, 9(6), 718–727. [https://doi.org/10.1016/S0959-4388\(99\)00028-8](https://doi.org/10.1016/S0959-4388(99)00028-8)
- Kawato, M., Furukawa, K., & Suzuki, R. (1987). A hierarchical neural-network model for control and learning of voluntary movement. *Biological Cybernetics*, 57(3), 169–185. <https://doi.org/10.1007/BF00364149>
- Kay, M. (2018). *Tidybayes: Tidy data and geoms for mcmc/bayesian samplers*. Retrieved from <https://github.com/mjskay/tidybayes>
- Key, B. L., Campbell, T. S., Bacon, S. L., & Gerin, W. (2008). The influence of trait and state rumination on cardiovascular recovery from a negative emotional stressor. *Journal of Behavioral Medicine*, 31, 237–248. <https://doi.org/10.1007/s10865-008-9152-9>
- Kline, R. (2004). *What's Wrong With Statistical Tests—And Where We Go From Here*. <https://doi.org/10.1037/10693-003>
- Kohler, C. G., Turner, T., Stolar, N. M., Bilker, W. B., Brensinger, C. M., Gur, R. E., & Gur, R. C. (2004). Differences in facial expressions of four universal emotions. *Psychiatry Research*, 128(3), 235–244. <https://doi.org/10.1016/j.psychres.2004.07.003>
- Koster, E. H. W., De Lissnyder, E., & De Raedt, R. (2013). Rumination is characterized by valence-specific impairments in switching of attention. *Acta Psychologica*, 144(3), 563–570. <https://doi.org/10.1016/j.actpsy.2013.09.008>
- Koster, E. H. W., De Lissnyder, E., Derakshan, N., & De Raedt, R. (2011). Understanding depressive rumination from a cognitive science perspective: The impaired disengagement hypothesis. *Clinical Psychology Review*, 31(1), 138–145. <https://doi.org/10.1016/j.cpr.2010.08.005>
- Kruschke, J. K. (2015). *Doing Bayesian data analysis: A tutorial with R, JAGS, and Stan* (Edition 2). Boston: Academic Press.
- Kruschke, J. K., & Liddell, T. M. (2018a). Bayesian data analysis for newcomers. *Psychonomic Bulletin & Review*, 25(1), 155–177. <https://doi.org/10.3758/s13423-017-1272-1>
- Kruschke, J. K., & Liddell, T. M. (2018b). The Bayesian New Statistics: Hypothesis testing, estimation, meta-analysis, and power analysis from a Bayesian perspective. *Psychonomic Bulletin & Review*, 25(1), 178–206. <https://doi.org/10.3758/s13423-016-1221-4>
- Kruschke, J. K., & Meredith, M. (2018). *BEST: Bayesian estimation supersedes the t-test*. Retrieved from <https://CRAN.R-project.org/package=BEST>
- Lambdin, C. (2012). Significance tests as sorcery: Science is empirical—significance tests are not. *Theory & Psychology*, 22(1), 67–90. <https://doi.org/10.1177/0959354311429854>

- Langland-Hassan, P., Faries, F. R., Richardson, M. J., & Dietz, A. (2015). Inner speech deficits in people with aphasia. *Frontiers in Psychology*, 6. <https://doi.org/10.3389/fpsyg.2015.00528>
- Laurent, L., Millot, J.-L., Andrieu, P., Camos, V., Flooccia, C., & Mathy, F. (2016). Inner speech sustains predictable task switching: Direct evidence in adults. *Journal of Cognitive Psychology*, (April), 1–8. <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 Rumination–Depression Relationship. *Cognitive Therapy and Research*, 42(4), 421–435. <https://doi.org/10.1007/s10608-018-9890-0>
- Lemoult, J., & Joormann, J. (2014). Depressive rumination alters cortisol decline in Major Depressive Disorder. *Biological Psychology*, 100, 50–55. <https://doi.org/10.1016/j.biopsych.2014.05.001>
- Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. Cambridge, MA, US: The MIT Press.
- Levelt, W. J. M. (2000). Producing spoken language: A blueprint of the speaker. In C. M. Brown & P. Hagoort (Eds.), *The Neurocognition of Language* (pp. 82–122). Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780198507932.003.0004>
- Levine, D. N., Calvanio, R., & Popovics, A. (1982). Language in the absence of inner speech. *Neuropsychologia*, 20(4), 391–409. [https://doi.org/10.1016/0028-3932\(82\)90039-2](https://doi.org/10.1016/0028-3932(82)90039-2)
- 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>
- Locke, J. L. (1970). Subvocal speech and speech. *ASHA*, 12, 7–14.
- Locke, J. L., & Fehr, F. S. (1970). Subvocal Rehearsal as a Form of Speech. *Journal of Verbal Learning and Verbal Behavior*, 9(5), 495–498. [https://doi.org/10.1016/s0022-5371\(70\)80092-5](https://doi.org/10.1016/s0022-5371(70)80092-5)
- Lüdecke, D. (2018). *Sjstats: Collection of convenient functions for common statistical computations*. Retrieved from <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>
- Lvenbruck, H. (2018). What the neurocognitive study of inner language reveals about our inner space. In S. Smadja & P.-L. Patoine (Eds.), *Épistémocritique, nř 18 : Langage intérieur - Espaces intérieurs / Inner Speech - Inner Space* (Vol. XVIII). Retrieved from <http://epistemocritique.org/what-the-neurocognitive-study-of-inner-language-reveals-about-our-inner-space>
- Lvenbruck, H., Grandchamp, R., Rapin, L., Nalborczyk, L., Dohen, M., Perrier, P., ... 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.

- Mackay, D. G. (1981). The Problem of Rehearsal or Mental Practice. *Journal of Motor Behavior*, 13(4), 274–285. <https://doi.org/10.1080/00222895.1981.10735253>
- MacKay, D. G. (1992). Constraints on theories of inner speech. In D. Reisberg (Ed.), *Auditory imagery* (pp. 121–149). Erlbaum; Hillsdale, N. J.
- Maier-Hein, L., Metze, F., Schultz, T., & Waibel, A. (2005). Session independent non-audible speech recognition using surface electromyography. In *IEEE Workshop on Automatic Speech Recognition and Understanding, 2005*. (pp. 331–336). San Juan, Puerto Rico: IEEE. <https://doi.org/10.1109/ASRU.2005.1566521>
- Makovac, E., Smallwood, J., Watson, D. R., Meeten, F., Critchley, H. D., & Ottaviani, C. (2018). The verbal nature of worry in generalized anxiety: Insights from the brain. *NeuroImage: Clinical*, 17, 882–892. <https://doi.org/10.1016/j.nicl.2017.12.014>
- 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>
- Marshall, R. C., Rappaport, B. Z., & Garcia-Bunuel, L. (1985). Self-monitoring behavior in a case of severe auditory agnosia with aphasia. *Brain and Language*, 24(2), 297–313. [https://doi.org/10.1016/0093-934X\(85\)90137-3](https://doi.org/10.1016/0093-934X(85)90137-3)
- 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.
- Martin, R. C., & Caramazza, A. (1982). Short-term memory performance in the absence of phonological coding. *Brain and Cognition*, 1(1), 50–70. [https://doi.org/10.1016/0278-2626\(82\)90006-9](https://doi.org/10.1016/0278-2626(82)90006-9)
- Martínez-Manrique, F., & Vicente, A. (2015). The activity view of inner speech. *Frontiers in Psychology*, 6, 232. <https://doi.org/10.3389/fpsyg.2015.00232>
- 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>
- McElreath, R. (2016). *Rethinking: Statistical rethinking book package*.
- 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>
- McNamara, A., Arino de la Rubia, E., Zhu, H., Ellis, S., & Quinn, M. (2018). *Skimr: Compact and flexible summaries of data*. Retrieved from <https://CRAN.R-project.org/package=skimr>

- Meehl, P. E. (1967). Theory-Testing in Psychology and Physics: A Methodological Paradox. *Philosophy of Science*, 34(2), 103–115. <https://doi.org/10.1086/288135>
- Meltzner, G. S., Sroka, J., Heaton, J. T., Gilmore, L. D., Colby, G., Roy, S., ... Luca, C. J. D. (2008). Speech Recognition for Vocalized and Subvocal Modes of Production Using Surface EMG Signals from the Neck and Face. In *INTERSPEECH* (pp. 2667–2670). Brisbane, Australia.
- Miller, E. K. (2000). The prefrontal cortex and cognitive control. *Nature Reviews Neuroscience*, 1(1), 59–65. <https://doi.org/10.1038/35036228>
- Morey, R. D., Hoekstra, R., Rouder, J. N., Lee, M. D., & Wagenmakers, E.-J. (2015). The fallacy of placing confidence in confidence intervals. *Psychonomic Bulletin & Review*, 23(1), 103–123. <https://doi.org/10.3758/s13423-015-0947-8>
- Moulton, S. T., & Kosslyn, S. M. (2009). Imagining predictions: Mental imagery as mental emulation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1521), 1273–1280. <https://doi.org/10.1098/rstb.2008.0314>
- Müller, K. (2017). *Here: A simpler way to find your files*. Retrieved from <https://CRAN.R-project.org/package=here>
- Nalborczyk, L., Batailler, C., Lvenbruck, H., Vilain, A., & Bürkner, P.-C. (2019a). 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*. https://doi.org/10.1044/2018_JSLHR-S-18-0006
- Nalborczyk, L., Bürkner, P. C., & Williams, D. R. (2019b). Pragmatism should not be a substitute for statistical literacy, a commentary on Albers, Kiers, and van Ravenzwaaij (2018). *Collabra: Psychology*, 5(1). <https://doi.org/10.1525/collabra.197>
- Nalborczyk, L., Perrone-Bertolotti, M., Baeyens, C., Grandchamp, R., Polosan, M., Spinelli, E., ... Lvenbruck, H. (2017). Orofacial electromyographic correlates of induced verbal rumination. *Biological Psychology*, 127, 53–63. <https://doi.org/10.1016/j.biopsych.2017.04.013>
- Netsell, R., Ashley, E., & Bakker, K. (2010). The inner speech of persons who stutter. In *Proceedings of the international motor speech conference*.
- 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>
- Nicenboim, B., & Vasishth, S. (2016). Statistical methods for linguistic research: Foundational Ideas-Part II: Statistical methods for linguistics—Part II. *Language and Linguistics Compass*, 10(11), 591–613. <https://doi.org/10.1111/lnc3.12207>
- 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.jfl.2005.09.002>

bandl.2005.11.007

Nisbett, J., & Wilson, T. D. (1977). Telling more than we can know: Verbal reports of mental processes. *Psychological Review*, 84(3), 231–259. <https://doi.org/10.1037//%200033-295x.84.3.231>

Nolen-Hoeksema, S. (1991a). 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. (1991b). 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., & Morrow, J. (1991). A Prospective Study of Depression and Posttraumatic Stress Symptoms After a Natural Disaster: The 1989 Loma Prieta Earthquake. *Journal of Personality and Social Psychology*, 61(1), 115–121. <https://doi.org/10.1037//0022-3514.61.1.115>

Nolen-Hoeksema, S., & Morrow, J. (1993). Effects of rumination and distraction on naturally occurring depressed mood. *Cognition and Emotion*, 7(6), 561–570. <https://doi.org/10.1080/02699939308409206>

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>

Olatunji, B. O., Naragon-Gainey, K., & Wolitzky-Taylor, K. B. (2013). Specificity of Rumination in Anxiety and Depression: A Multimodal Meta-Analysis. *Clinical Psychology: Science and Practice*, 20(3), 225–257. <https://doi.org/10.1111/cpsp.12037>

Oppenheim, G. M., & Dell, G. S. (2008). Inner speech slips exhibit lexical bias, but not the phonemic similarity effect. *Cognition*, 106(1), 528–537. <https://doi.org/10.1016/j.cognition.2007.02.006>

Oppenheim, G. M., & Dell, G. S. (2010). Motor movement matters: The flexible abstractness of inner speech. *Memory & Cognition*, 38(8), 1147–1160. <https://doi.org/10.3758/MC.38.8.1147>

O’Shea, H., & Moran, A. (2017). Does Motor Simulation Theory Explain the Cognitive Mechanisms Underlying Motor Imagery? A Critical Review. *Frontiers in Human Neuroscience*, 11. <https://doi.org/10.3389/fnhum.2017.00072>

Ottaviani, C., Shahabi, L., Tarvainen, M., Cook, I., Abrams, M., & Shapiro, D. (2015). Cognitive, behavioral, and autonomic correlates of mind wandering and perseverative cognition in major depression. *Frontiers in Neuroscience*, 8(January), 1–9. <https://doi.org/10.3389/fnins.2014.00433>

Palmer, E. D., Rosen, H. J., Ojemann, J. G., Buckner, R. L., Kelley, W. M., & Petersen, S. E. (2001). An Event-Related fMRI Study of Overt and Covert Word Stem Completion. *NeuroImage*, 14(1), 182–193. <https://doi.org/10.1006/nimg.2001.0779>

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](https://doi.org/10.1002/(SICI)1099-0879(199905)6:2%3C156::AID-CPP196%3E3.0.CO;2-A)
- Paulesu, E., Frith, C. D., & Frackowiak, R. S. J. (1993). The neural correlates of the verbal component of working memory. *Nature*, 362(6418), 342–345. <https://doi.org/10.1038/362342a0>
- 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*. Retrieved from <https://github.com/thomasp85/patchwork>
- Penney, A. M., Miedema, V. C., & Mazmanian, D. (2015). Intelligence and emotional disorders : Is the worrying and ruminating mind a more intelligent mind ? *Personality and Individual Differences*, 74, 90–93. <https://doi.org/10.1016/j.paid.2014.10.005>
- Perrone-Bertolotti, M., Rapin, L., Lachaux, J. P., Baciu, M., & Lvenbruck, 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>
- Phinyomark, A., Nuidod, A., Phukpattaranont, P., & Limsakul, C. (2012). Feature Extraction and Reduction of Wavelet Transform Coefficients for EMG Pattern Classification. *Electronics and Electrical Engineering*, 122(6). <https://doi.org/10.5755/j01.eee.122.6.1816>
- Pickering, M. J., & Garrod, S. (2013). An integrated theory of language production and comprehension. *Behavioral and Brain Sciences*, 36(04), 329–347. <https://doi.org/10.1017/S0140525X12001495>
- 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>
- Pruitt, T. A., Halpern, A. R., & Pfardresher, P. Q. (2018). Covert singing in anticipatory auditory imagery. *Psychophysiology*, e13297. <https://doi.org/10.1111/psyp.13297>
- 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>
- Raez, M. B. I., Hussain, M. S., & Mohd-Yasin, F. (2006). Techniques of EMG signal analysis: Detection, processing, classification and applications. *Biological Procedures Online*, 8, 11–35. <https://doi.org/10.1251/bpo115>
- Randenborgh, A. van, Hüffmeier, J., LeMoult, J., & Joormann, J. (2010). Letting go of unmet goals: Does self-focused rumination impair goal disengagement? *Motivation and Emotion*, 34, 325–332. <https://doi.org/10.1007/s11031-010-9190-9>
- Rapin, L. (2011). *Hallucinations auditives verbales et trouble du langage intérieur dans la schizophrénie: Traces physiologiques et bases cérébrales* (PhD thesis). University of Grenoble.

- Rapin, L., Dohen, M., Polosan, M., & Perrier, P. (2013a). An EMG Study of the Lip Muscles During Covert Auditory Verbal Hallucinations in Schizophrenia. *JSLHR*, 56, 1882–1893. [https://doi.org/10.1044/1092-4388\(2013/12-0210\)and](https://doi.org/10.1044/1092-4388(2013/12-0210)and)
- Rapin, L., Dohen, M., Polosan, M., Perrier, P., & Lvenbruck, H. (2013b). An EMG study of the lip muscles during covert auditory verbal hallucinations in schizophrenia. *Journal of Speech, Language, and Hearing Research : JSLHR*, 56(6), S1882–93. [https://doi.org/10.1044/1092-4388\(2013/12-0210\)](https://doi.org/10.1044/1092-4388(2013/12-0210))
- R Core Team. (2018). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from <https://www.R-project.org/>
- Regalo, S. C. H., Vitti, M., Moraes, M. T. B., Semprini, M., Felício, C. M. de, Mattos, M. da G. C. de, ... Santos, C. M. (2005). Electromyographic analysis of the orbicularis oris muscle in oralized deaf individuals. *Brazilian Dental Journal*, 16(3), 237–242. <https://doi.org/10.1590/S0103-64402005000300012>
- Rippere, V. (1977). What's the thing to do when you're feeling depressed? A cross-cultural replication. *Behaviour Research and Therapy*, 15, 185–191. [https://doi.org/10.1016/0005-7967\(83\)90038-4](https://doi.org/10.1016/0005-7967(83)90038-4)
- 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>
- Rood, L., Roelofs, J., Bögels, S. M., & Arntz, A. (2012). The effects of experimentally induced rumination, positive reappraisal, acceptance, and distancing when thinking about a stressful event on affect states in adolescents. *Journal of Abnormal Child Psychology*, 40(1), 73–84. <https://doi.org/10.1007/s10802-011-9544-0>
- Rossini, P. M. (1999). Corticospinal Excitability Modulation to Hand Muscles During Movement Imagery. *Cerebral Cortex*, 9(2), 161–167. <https://doi.org/10.1093/cercor/9.2.161>
- Salahuddin, L., Cho, J., Jeong, M. G., & Kim, D. (2007). Ultra short term analysis of heart rate variability for monitoring mental stress in mobile settings. *Conference Proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference*, 2007, 4656–4659. <https://doi.org/10.1109/IEMBS.2007.4353378>
- Schönbrodt, F. D., & Wagenmakers, E.-J. (2018). Bayes factor design analysis: Planning for compelling evidence. *Psychonomic Bulletin & Review*, 25(1), 128–142. <https://doi.org/10.3758/s13423-017-1230-y>
- Schönbrodt, F. D., Wagenmakers, E.-J., Zehetleitner, M., & Perugini, M. (2017). Sequential Hypothesis Testing With Bayes Factors: Efficiently Testing Mean Differences. *Psychological Methods*, 22(2), 322–339. <https://doi.org/10.1037/met0000061>
- 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>

- Shuster, L., & Lemieux, S. (2005). An fMRI investigation of covertly and overtly produced mono- and multisyllabic words. *Brain and Language*, 93(1), 20–31. <https://doi.org/10.1016/j.bandl.2004.07.007>
- Sibrava, N. J., & Borkovec, T. D. (2006). The Cognitive Avoidance Theory of Worry. In G. C. L. Davey & A. Wells (Eds.), *Worry and its Psychological Disorders* (pp. 239–256). Chichester, UK: John Wiley & Sons Ltd. <https://doi.org/10.1002/9780470713143.ch14>
- Siegle, G. J., & Thayer, J. F. (2003). Physiological Aspects of Depressive Rumination. In C. Papageorgiou & A. Wells (Eds.), *Depressive Rumination* (pp. 79–104). Chichester, UK: John Wiley & Sons Ltd. <https://doi.org/10.1002/9780470713853.ch5>
- Sigmon, S. T., Dorhofer, D. M., Rohan, K. J., & Boulard, N. E. (2000). The Impact of Anxiety Sensitivity, Bodily Expectations, and Cultural Beliefs on Menstrual Symptom Reporting: A Test of the Menstrual Reactivity Hypothesis. *Journal of Anxiety Disorders*, 14(6), 615–633. [https://doi.org/10.1016/s0887-6185\(00\)00054-2](https://doi.org/10.1016/s0887-6185(00)00054-2)
- 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>
- Simonyan, K., & Horwitz, B. (2011). Laryngeal Motor Cortex and Control of Speech in Humans. *The Neuroscientist*, 17(2), 197–208. <https://doi.org/10.1177/1073858410386727>
- Slowikowski, K. (2018). *Ggrepel: Automatically position non-overlapping text labels with 'ggplot2'*. Retrieved from <https://CRAN.R-project.org/package=ggrepel>
- 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>
- Smith, S. M., Brown, H. O., Toman, J. E. P., & Goodman, L. S. (1947). The lack of cerebral effects of d-tubocurarine. *Anesthesiology*, 8(1), 1–14.
- Sokolov, A. (1972). *Inner speech and thought*. New York: Springer-Verlag.
- Sorensen, T., Hohenstein, S., & Vasishth, S. (2016). Bayesian linear mixed models using Stan: A tutorial for psychologists, linguists, and cognitive scientists. *The Quantitative Methods for Psychology*, 12(3), 175–200. <https://doi.org/10.20982/tqmp.12.3.p175>
- Sinear, C. M. (2010). Corticospinal facilitation during motor imagery. In A. Guillot & C. Collet (Eds.), *The neurophysiological foundations of mental and motor imagery*. Oxford University Press.
- Stricker, S. (1880). *Studien über die Sprachvorstellungen*. Wien: Braumüller.
- Sumitsuji, N., Matsumoto, K., Tanaka, M., Kashiwagi, T., & Kaneko, Z. (1967). Electromyographic investigation of the facial muscles. *Electromyography*, 7(2), 77–96.
- Tassinary, L. G., Cacioppo, J. T., & Vanman, E. J. (2007). The Skeletomotor System. In G. Berntson, J. T. Cacioppo, & L. G. Tassinary (Eds.), *Handbook of Psychophysiology* (3rd ed., pp. 267–300). Cambridge: Cambridge University Press. Retrieved from <https://www.cambridge.org/core/books/handbook-of-psychophysiology/skeletomotor-system/CAD1D438D70B4242013F71848E4799D0>

- Trafimow, D., Amrhein, V., Areshenkoff, C. N., Barrera-Causil, C. J., Beh, E. J., Bilgiç, Y. K., ... Marmolejo-Ramos, F. (2018). Manipulating the Alpha Level Cannot Cure Significance Testing. *Frontiers in Psychology*, 9. <https://doi.org/10.3389/fpsyg.2018.00699>
- Treynor, W., Gonzalez, R., & Nolen-Hoeksema, S. (2003). Rumination Reconsidered : A Psychometric Analysis, 27(3), 247–259. <https://doi.org/10.1023/A:1023910315561>
- Uttl, B., Morin, A., & Hamper, B. (2011). Are Inner Speech Self-Report Questionnaires Reliable and Valid? *Procedia - Social and Behavioral Sciences*, 30, 1719–1723. <https://doi.org/10.1016/j.sbspro.2011.10.332>
- Vallar, G., & Cappa, S. F. (1987). Articulation and verbal short-term memory: Evidence from anarthria. *Cognitive Neuropsychology*, 4(1), 55–77. <https://doi.org/10.1080/02643298708252035>
- Vickers, K. S., & Vogeltanz-Holm, N. D. (2003). The Effects of Rumination and Distraction Tasks on Psychophysiological Responses and Mood in Dysphoric and Nondysphoric Individuals. *Cognitive Therapy and Research*, 19.
- Vygotsky, L. S. (1987). *The Collected Works of L. S. Vygotsky*. (R. W. Rieber & A. S. Carton, Eds.). Springer US.
- Wagenmakers, E.-J., Lodewyckx, T., Kuriyal, H., & Grasman, R. (2010). Bayesian hypothesis testing for psychologists: A tutorial on the Savage–Dickey method. *Cognitive Psychology*, 60(3), 158–189. <https://doi.org/10.1016/j.cogpsych.2009.12.001>
- Wasserstein, R. L., & Lazar, N. A. (2016). The ASA's Statement on *p*-Values: Context, Process, and Purpose. *The American Statistician*, 70(2), 129–133. <https://doi.org/10.1080/00031305.2016.1154108>
- Wasserstein, R. L., Schirm, A. L., & Lazar, N. A. (2019). Moving to a World Beyond “*p* < 0.05”. *The American Statistician*, 73(sup1), 1–19. <https://doi.org/10.1080/00031305.2019.1583913>
- Watkins, E. R. (2008). Constructive and unconstructive repetitive thought. *Psychological Bulletin*, 134(2), 163–206. <https://doi.org/10.1037/0033-2909.134.2.163>
- Watkins, E. R., Moulds, M., & 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>
- Watson, J. B. (1919). *Psychology from the standpoint of a behaviorist*. Philadelphia, PA, US: J B Lippincott Company. <https://doi.org/10.1037/10016-000>
- Wickham, H. (2017). *Tidyverse: Easily install and load the 'tidyverse'*. Retrieved from <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*. Retrieved from <https://CRAN.R-project.org/package=ggplot2>

- Wolpert, D., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, 269(5232), 1880–1882. <https://doi.org/10.1126/science.7569931>
- 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>
- Woody, M. L., McGeary, J. E., & Gibb, B. E. (2014). Brooding rumination and heart rate variability in women at high and low risk for depression: Group differences and moderation by COMT genotype. *Journal of Abnormal Psychology*, 123(1), 61–67. <https://doi.org/10.1037/a0035450>
- Xie, Y. (2018). *Knitr: A general-purpose package for dynamic report generation in r*. Retrieved from <https://CRAN.R-project.org/package=knitr>
- Zivin, G. (1979). *The development of self-regulation through private speech*. New York: Wiley.
- 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/smj.2588>