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1 **The role of motor inhibition during covert speech production**

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12

Abstract

13 Covert speech is accompanied by a subjective multisensory experience with auditory and
14 kinaesthetic components. An influential hypothesis states that these sensory percepts
15 result from a simulation of the corresponding motor action that relies on the same
16 internal models recruited for the control of overt speech. This simulationist view raises
17 the question of how it is possible to imagine speech without executing it. In this
18 perspective, we discuss the possible role(s) played by motor inhibition during covert
19 speech production. We suggest that considering covert speech as an inhibited form of
20 overt speech maps naturally to the purported progressive internalisation of overt speech
21 during childhood. However, we argue that the role of motor inhibition may differ widely
22 across different forms of covert speech (e.g., condensed vs. expanded covert speech) and
23 that considering this variety helps reconciling seemingly contradictory findings from the
24 neuroimaging literature.

25 *Keywords:* covert speech, inner speech, motor imagery, motor simulation, motor
26 control, motor inhibition

1 Introduction

27

28 The ability to mentally examine our verbal thoughts is central to our subjective
29 experience. This covert (internal) production of speech typically accompanies everyday
30 activities such as problem solving (Baldo et al., 2005; Sokolov, 1972), future planning
31 (D’Argembeau et al., 2011), reading (e.g., Lœvenbruck et al., 2005; Perrone-Bertolotti
32 et al., 2012), or writing (Frith, 1979). Because *overt* speech production results from
33 sequences of motor commands that are assembled to reach a given communication goal, it
34 belongs to the broader category of motor actions (Jeannerod, 2006a). Therefore, a
35 parallel can be drawn between covert speech, also known as *inner speech* or *speech*
36 *imagery* (for reviews, see Alderson-Day & Fernyhough, 2015; Lœvenbruck et al., 2018;
37 Perrone-Bertolotti et al., 2014), and other imagined actions (i.e., motor imagery). The
38 motor simulation theory of motor imagery (Jeannerod, 1994, 2001, 2006b) postulates a
39 continuum between the covert and the overt execution of an action and that action
40 representations can operate off-line via a simulation mechanism.

41 However, the proposal that overt and covert actions share common processes and
42 neural circuits is faced with a serious problem. If the neural circuits used for the control
43 of overt actions are also used for covert actions, how can covert actions not lead to
44 execution? This puzzle was coined as *the problem of inhibition* by Jeannerod (2001). It
45 can be rephrased as follows: given the putative role of the motor system in providing the
46 multisensory content of motor imagery, how is it possible for motor imagery not to lead
47 to motor execution? In this perspective, we examine some theoretical and experimental
48 consequences that emerge from considering covert speech as inhibited overt speech. First,
49 we explore the role and plausible neural implementation of inhibitory mechanisms during
50 covert speech production. Second, we relate the maturation of inhibitory control during
51 childhood with the progressive internalisation of overt speech. Third, we consider how
52 inhibitory mechanisms may play different roles across different forms of covert speech. By
53 bridging recent results from the covert speech, motor imagery, and motor inhibition
54 literature, we highlight some novel and possibly fruitful lines of research.

2 Covert speech production as inhibited overt speech production

2.1 Cognitive and neural mechanisms supporting motor inhibition

First and foremost, we need to make a distinction between at least two different types of inhibition. First, cognitive inhibition, defined as the stopping or overriding of a mental process, with or without intention (MacLeod, 2007). Second, the inhibition of physical response, or motor inhibition, defined broadly as the withholding, suppression, or overriding of an inappropriate, prepotent, or unwanted motor response (Aron, 2007; O'Shea & Moran, 2018). Here, we are concerned with the latter. Ridderinkhof et al. (2014) further described the concept of response inhibition on three continuous dimensions: intentionality, premeditation, and specificity. Inhibition can be employed with more or less intentionality, planned ahead or employed in the moment, and applied to a specific action and effector, or more globally, to all actions and/or effectors.

Within Ridderinkhof et al.'s classification of response inhibitions, we hypothesise that covert speech involves an intentional (we know we want to produce these actions covertly rather than overtly) but implicit/automatic (we do not explicitly think about not producing movements) and planned ahead form of response inhibition. The distinction between implicit and explicit inhibition seems important to highlight. Indeed, the type of motor inhibition that may be at play during motor imagery is still different from the "proactive inhibition" in the motor inhibition literature. Indeed, in behavioural tasks aiming to assess proactive inhibition, participants are instructed not to execute an action. In contrast, while doing motor imagery, participants are asked to imagine the action, which implies that it should not be executed overtly (Guillot et al., 2012). Moreover, the type of motor inhibition that is implemented during covert speech necessarily has to be planned ahead, otherwise speech acts would sometimes be (at least partially) executed. Regarding the level at which motor inhibition may be applied during covert speech, we hypothesise that inhibition may apply both globally and in an effector-specific manner. Supporting this hypothesis, Rieger et al. (2017) and Bart et al. (2021) have shown, using an action mode (overt vs. covert) switching paradigm, that the motor imagery of hand movements is accompanied by both global and effector-specific

84 inhibition (these results were also replicated in Scheil & Liefoghe, 2018).

85 Based on evidence from electrophysiological, neuroimaging, and clinical studies,
86 Guillot et al. (2012) suggested three possible routes whereby motor commands can be
87 inhibited during motor imagery. First, motor inhibition can be integrated within the
88 representation of the action to be produced internally. Second, cerebral regions such as
89 the supplementary motor area (SMA) (Kasess et al., 2008) or the right inferior frontal
90 gyrus (rIFG) may weaken the motor commands that are emitted during motor imagery
91 (e.g., Angelini et al., 2015, 2016). More precisely, the pre-SMA and the rIFG may work
92 together to intercept the action process via the basal ganglia (subthalamic nucleus, STN),
93 hence suppressing the output from the basal ganglia which in turn might inhibit the
94 primary motor cortex (Aron, 2011) (cf. Figure 1). In addition to inter-regional inhibitory
95 influences, motor imagery has been shown to be associated with modulations of
96 short-interval intracortical inhibition within the primary motor cortex itself (Neige et al.,
97 2020). Third, downstream regions in the cerebellum (e.g., Lotze et al., 1999), in the
98 brainstem (e.g., Jeannerod, 2001, 2006a), or at the spinal level may contribute to motor
99 inhibition at a later stage.

100 Whether motor commands are emitted and subsequently inhibited during covert
101 speech production is an issue that has been debated (e.g., Geva, 2018). It has been
102 suggested that during covert speech production, motor commands would be "simply
103 specified in sub-threshold way, requiring no active inhibition" (Geva, 2018). Alternatively,
104 motor commands may be emitted but subsequently inhibited by frontal regions (e.g.,
105 Grandchamp et al., 2019; Løevenbruck et al., 2018). However, stating that covert speech
106 (or motor imagery, more generally) only involves subthreshold activity (and therefore is
107 not accompanied by the emission of motor commands that are inhibited) simply shifts
108 the problem from "how and where motor commands are subsequently inhibited" to "how
109 and where the magnitude of activity in the motor system is planned or monitored" (see
110 also Scheil & Liefoghe, 2018). In other words, we still need to explain how (in a
111 mechanistic and/or developmental way) this activity is maintained at a subthreshold
112 level. What cognitive and neural mechanisms operate to maintain this activity under the

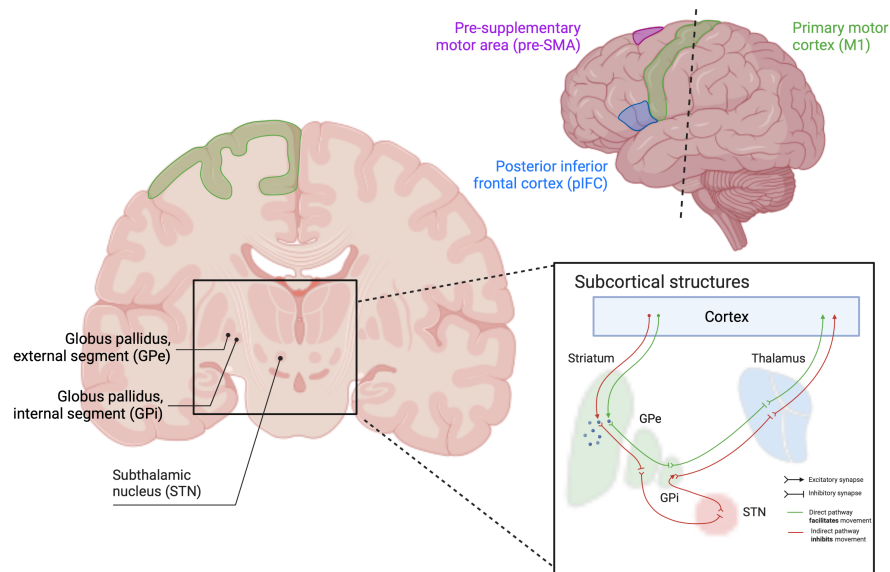


Figure 1

Plausible implementation of the cortical and subcortical inhibitory mechanisms responsible for the "proactive" (but implicit) response inhibition at play during covert speech production. The pre-SMA, posterior rIFC, and STN together form an inhibitory network known as the inhibitory triangle, which may be responsible for braking motor commands during covert speech production. Figure created with BioRender.com.

113 threshold? In this section, we provided empirical arguments in favour of the "active
 114 inhibition hypothesis". Proponents of the "subliminal level hypothesis" need to clarify
 115 how this activity is maintained at a subthreshold level during covert speech production,
 116 thus preventing execution.

117 The putative involvement and functional role of inhibitory mechanisms during
 118 covert speech could be assessed in several ways. First, it could be assessed by
 119 experimentally manipulating the activity of the inhibitory network responsible for
 120 preventing execution during motor imagery. For instance, transcranial magnetic
 121 stimulation (TMS) could be used to interrupt these inhibitory mechanisms and thus
 122 facilitate execution during motor imagery. Second, the role of inhibitory mechanisms
 123 during covert verbal actions could be examined in populations with well-identified
 124 inhibitory deficits. For instance, Tourette syndrome is a childhood-onset neurological

125 disorder affecting approximately 1% of children and characterised by chronic motor and
126 phonic tics (Jackson et al., 2015). Verbal tics can consist of repeating sounds, words, or
127 utterances (palilalia), producing inappropriate or obscene utterances (coprolalia), or the
128 repetition of another's words (echolalia). In their review, Jackson et al. (2015) suggested
129 that increased control over motor outputs, acquired by repeatedly trying to suppress tics,
130 is brought about by local increases in GABAergic "tonic" inhibition within regions such
131 as the SMA, leading to localised reductions in the gain of motor excitability. For these
132 reasons, comparing the neural implementation of inhibitory mechanisms during covert
133 speech in patients with Tourette syndrome and healthy controls may shed light on the
134 role and flexibility of these mechanisms.

135 **2.2 Covert speech development: Learning not to produce speech**

136 Watson (1919) suggested that thought was rooted in overt speech. In his
137 terminology, thought referred to covert speech. Hence, his view was that covert speech
138 matures from overt speech. Vygotsky (1934) further formulated the idea that covert
139 speech is internalised during childhood from private egocentric speech, that is, from
140 self-addressed overt speech. Fernyhough (2004) extended these ideas by proposing four
141 levels of internalisation: external dialogue, private speech, expanded inner speech, and
142 condensed inner speech. These levels represent stages of development but also define
143 movements between levels, that is, how a speaker may go from overt to covert speech and
144 conversely. The level at which speech is expressed may depend on inhibitory control
145 applied at different levels in the production flow, such as the formulation or the
146 articulatory planning level (Grandchamp et al., 2019). Therefore, producing covert
147 speech crucially depends on successfully inhibiting speech production at several levels.

148 We formulate the hypothesis that the progressive internalisation of speech during
149 childhood may be related to the development of inhibitory abilities. This hypothesis
150 could be tested in several ways. First, the relation between speech internalisation and
151 inhibitory abilities could be assessed during development at the critical ages (i.e., between
152 6 and 8 years). We would expect the ability to imagine actions, and speech specifically, to

153 be positively correlated with inhibitory skills at this age. Wang et al. (2021) provided
154 correlational evidence that motor imagery (as assessed by a hand laterality judgement
155 task and alphanumeric rotation task) and motor inhibition performance (as assessed by a
156 stop-signal task) improve together between 7 and 11 years old, and that these two
157 abilities correlated at 7 years old but did not correlate at 11 years old. This suggests that
158 inhibitory control may play a peculiar role when speech is being internalised, but its role
159 may weaken with expertise. This is consistent with results from training studies
160 suggesting that, with growing expertise, we tend to rely more and more on memory-based
161 processes to produce mental imagery (e.g., Jolicoeur, 1985; Tarr & Pinker, 1989).

162 Second, the hypothesised co-development of motor imagery and response
163 inhibition abilities could be tested by examining how novel actions are internalised in
164 adults. For instance, let's consider the analogy between speaking and playing a music
165 instrument (e.g., playing the piano). The act of producing speech can be paralleled with
166 the act of playing an instrument. Both actions consist in the coordination of complex
167 movements that result in some modifications of the environment, that in turn generate
168 sensory feedback (e.g., kinaesthetic, auditory) for the agent. This analogy suggests that
169 we might be able to study the development of internal models responsible for the sensory
170 experience accompanying imagined actions in the adult mind (e.g., when an individual is
171 learning either a novel music instrument or a new language with speech sounds that are
172 not present in his/her native language). By examining the development of novel imagined
173 actions in the adult mind and by using motor interference (e.g., articulatory suppression)
174 procedures, we might gain new insights about the internalisation of speech during
175 childhood.¹

¹ While keeping in mind the obvious limitation that the child mind is not equivalent to the adult mind, nor is it equivalent to a smaller version of the adult mind. Nevertheless, examining the development of novel imagined actions in adults avoids the contamination of the process of interest (imagined action) by developmental confounds.

176 **2.3 Does covert speech always involve motor inhibition?**

177 The production of covert speech is often, although not always and not for
178 everyone, accompanied by the feeling of hearing speech (Hurlburt, 2011). In other words,
179 covert speech is accompanied by a sensory experience that "feels like" hearing speech.
180 However, covert speech may also be accompanied by the feeling of producing speech.
181 These two facets of covert speech are characterised by different phenomenological
182 experiences. In this section, we discuss how these two forms of covert speech may require
183 motor inhibition to a different extent.

184 The dual stream prediction model (Tian & Poeppel, 2012, 2013; Tian et al., 2016)
185 describes two neural pathways that may provide the auditory content of covert speech.
186 First, the simulation-estimation prediction stream implements a motor-to-sensory
187 transformation via motor simulation, that is, by simulating speech movements and the
188 perceptual changes that would be associated with these movements (see also Løevenbruck
189 et al., 2018, for a similar proposal). This stream includes cerebral areas involved in
190 speech motor preparation such as the supplementary motor area, the inferior frontal
191 gyrus, the premotor cortex and the insula, as well as brain areas involved in
192 somatosensory estimation and perception such as primary and secondary somatosensory
193 regions, the parietal operculum, and the supramarginal gyrus (Tian et al., 2016). Second,
194 the memory-retrieval prediction stream may be used to provide auditory percepts by
195 "reconstructing stored perceptual information in modality-specific cortices" (Tian et al.,
196 2016). This mechanism provides sensory percepts without the need for computing the
197 predicted sensory consequences of (non executed) motor commands. Auditory percepts
198 may be retrieved from various memory sources, relying (amongst others) on the
199 hippocampal structures (Tian et al., 2016). Auditory percepts may also be retrieved from
200 a broad fronto-temporo-parietal lexico-semantic network (for more details, see Tian et al.,
201 2016).

202 The balance between these two mechanisms (i.e., simulation vs. memory retrieval)
203 may depend on the circumstances promoting covert speech or, in the lab, on the precise
204 instructions given to the participants, which may cue them to produce different forms of

205 covert speech. For instance, either one of these two streams may be preferentially
206 recruited depending on whether participants are instructed to "imagine speaking" or to
207 "imagine hearing" (see also the distinction between the "inner ear" and the "inner voice",
208 e.g., Smith et al., 1992). In line with this hypothesis, Tian et al. (2016) have shown that
209 inner speaking more strongly recruits brain regions in the simulation stream than inner
210 hearing, which more strongly recruits brain regions in the memory-retrieval stream. Ma
211 and Tian (2019) have shown that inner speaking and inner hearing have distinct
212 magnetoencephalographic (MEG) correlates and distinct effects on a subsequent phonetic
213 categorisation task (discriminating /ba/ vs. /da/).

214 In line with Tian and Poeppel (2012), we suggest that the balance between these
215 two mechanisms may also depend on situational (e.g., surrounding noise) and intrinsic
216 (e.g., expertise) characteristics. We further suggest that a common currency determining
217 the use of either one of these mechanisms is the computational cost of (or equivalently,
218 the computational resources available for) each alternative. To clarify, we borrow the
219 concept of memoisation as applied to cognition and mental imagery by Dasgupta and
220 Gershman (2021) (cf. Box 1). In these authors' view, memory can be considered as a
221 computational resource to facilitate computational reuse through memoisation. In the
222 context of motor and speech imagery, memoisation can be seen in the increasing reliance
223 on memory in the course of learning.

224 In other words, situational (extrinsic) and individual (intrinsic) characteristics
225 jointly determine the computational cost of (or equivalently, the available computational
226 resources for) the task, which in turn determines the balance between the simulation and
227 association mechanisms. For instance, we hypothesise that novel and/or difficult tasks
228 (which are both computationally more expensive, *ceteris paribus*) may rely more on the
229 simulation mechanism, whereas well known and/or easy tasks may rely more on
230 associative mechanisms. This idea is supported by several studies showing a greater
231 increase in facial EMG activity during the reading of difficult text or while performing
232 difficult mental arithmetic tasks, compared to easier tasks (e.g., Faaborg-Andersen et al.,
233 1958; Sokolov, 1972), suggesting a greater involvement of the speech motor system.

Box 1: Memoisation

Memoisation is a programming technique used to speed-up algorithms or programs. It avoids redundant computation by storing computational results and reusing them later. When calling a function (where a function can be a motor primitive), the function call is intercepted by a *memoiser* that inspects the previous calls of a function and its outputs. If a function has already been called with the same input, then the previously computed output is retrieved and reused.

In the context of covert speech, memoisation can be postulated as the process by which covert speech percepts produced by motor simulation are stored for later retrieval and use without invoking the motor simulation mechanism.

234 Alternatively, these results may suggest a lesser involvement of inhibitory mechanisms
235 (see also the discussion in Nalborczyk, 2019, 2020). This is congruent with the greater
236 reliance on associative mechanisms with greater expertise, as discussed previously.

237 To sum up, whereas inner speaking may involve active inhibition of motor
238 commands, inner hearing may not. These disparities between inner speaking and inner
239 hearing may explain the variety of neural correlates reported for covert speech production
240 (as reviewed for instance in Geva, 2018). More generally, different forms of covert speech,
241 that may vary in condensation (from thinking without words to thinking in words),
242 dialogicality (whether covert speech features monologues or dialogues), or intentionality
243 (for more details, see Grandchamp et al., 2019), may require inhibitory control to a
244 different extent, from no inhibition at all for condensed forms of covert speech to active
245 inhibition of motor commands for fully expanded forms of covert speech.

3 Conclusions

246
247 We explored some of the theoretical and experimental consequences that emerge
248 from considering covert speech production as an inhibited form of overt speech
249 production. To this end, we connected results from the motor imagery, motor inhibition,
250 and covert speech domains. Regarding the role and implementation of general-purpose

251 inhibitory mechanisms during the production of covert speech, we suggested that these
252 may be similar to the inhibitory network responsible for proactive response inhibition and
253 we summarised some propositions from this literature. We related the development of
254 response inhibition abilities in childhood development with the purported internalisation
255 of private speech around the same period. From the response inhibition perspective, the
256 internalisation of speech from overt to covert speech may essentially be considered as
257 "learning not to produce speech".

258 Regarding the neural origin of the sensory experience of covert speech, we
259 discussed the dual stream prediction model (Tian & Poeppel, 2012, 2013; Tian et al.,
260 2016), which suggests that these sensory percepts may be provided either by a
261 motor-simulation process or by a memory-retrieval process. We suggested that the
262 balance between these two mechanisms may be determined by task instructions, which
263 may prompt different forms of covert speech, and also by the computational cost of the
264 task. More precisely, novel or more difficult tasks are expected to rely more on the
265 motor-simulation mechanisms whereas well-known and/or easy tasks may rely more on a
266 "memoised version" of the motor simulation: the memory-retrieval prediction stream.
267 Whereas the former mechanism should involve active inhibitory mechanisms, the latter
268 should not, as there should be no (or less) motor commands to inhibit.

269 These propositions pave the way for several lines of research that should
270 consolidate our understanding of the relations between overt and covert speech
271 production. Several outstanding questions remain. Amongst others, how does the
272 development of inhibitory control relate with the progressive internalisation of speech
273 during childhood? How do individual and situational constraints shape the role of motor
274 inhibition during covert speech production? How is covert speech affected by poor or
275 degraded inhibitory control? Can we experimentally force the externalisation of speech in
276 adults, for example through neurostimulation? The use of neurostimulation and the
277 comparison between healthy controls and patients with well-identified inhibitory deficits
278 could help refine the involvement of these inhibitory mechanisms during covert speech
279 production, which may lead to applied outcomes in the care of motor and verbal tics.

Conflict of Interest Statement

280

281 The authors declare that the research was conducted in the absence of any
282 commercial or financial relationships that could be construed as a potential conflict of
283 interest.

Author Contributions

284

285 Conceptualisation: all authors; Funding acquisition: LN, ML, FXA; Supervision:
286 UD, ML, AG, FXA; Writing - original draft: LN; Writing - review and editing: all
287 authors.

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Data Availability Statement

293

294 No novel data were used in this paper. However, the source (\LaTeX) code is
295 available at <https://osf.io/dsfgb/>.

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