Abstract

Humans have the ability to mentally examine speech. This covert form of speech production is often accompanied by sensory (e.g., auditory) percepts. However, the cognitive and neural mechanisms that generate these percepts are still debated. According to a prominent proposal, inner speech has at least two distinct phenomenological components: inner speaking and inner hearing. Here we use transcranial magnetic stimulation to test whether these two phenomenologically distinct processes are supported by distinct neural mechanisms. We hypothesise that inner speaking relies more strongly on an online motor-to-sensory simulation that constructs a multisensory experience, whereas inner hearing relies more strongly on a memory-retrieval process, where the multisensory experience is reconstructed from stored motor-to-sensory associations. We predict that the speech motor system will be involved more strongly during inner speaking than inner hearing. This would be revealed by modulations of TMS evoked responses at muscle level following stimulation of the lip primary motor cortex.

Keywords: inner speech, inner speaking, inner hearing, transcranial magnetic stimulation, motor evoked potential

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Introduction

Rehearsing a conversation, preparing a public talk, or reading a novel are routine mental activities that are usually accompanied by an inner voice (Levine et al., 1982; Morin, 2012; Marcela Perrone-Bertolotti et al., 2012; Petkov & Belin, 2013; Sokolov, 1972). This inner voice feels like speech was produced or heard internally (e.g., Hurlburt & Heavey, 2015). In other words, it involves a conscious multisensory (e.g., auditory, kinaesthetic) experience (for reviews, see Alderson-Day & Fernyhough, 2015; M. Perrone-Bertolotti et al., 2014). Although commonly described as a unitary construct, inner speech may be better defined as a collection of distinct but related phenomenological experiences (e.g., Hurlburt, 2011; Hurlburt & Akhter, 2006). According to Hurlburt (2011), it is possible to distinguish the phenomenon of *inner speaking* from the phenomenon of *inner hearing*, whose feelings would be similar to talking in a tape recorder and hearing one's voice played back, respectively (Hurlburt et al., 2013).¹ The present research aims at better understanding the origins of the voice we experience during inner speaking and inner hearing, that is, the neurocognitive mechanisms through which it arises.

Stemming upon classical models of motor control, Loevenbruck et al. (2018) presented a predictive model of *wilful (expanded) inner speech* production (i.e., inner speaking). In this model, the auditory and kinaesthetic sensations perceived during inner speech are thought to be the predicted sensory consequences of (a copy of) inhibited speech motor acts. More precisely, these percepts are simulated by internal forward models that use the efference copies issued from an inverse model. According to this view, the primary motor cortex would be involved during inner speech production, but its output would be inhibited by prefrontal regions involved in response inhibition, such as the right inferior

¹ The distinction between inner speaking and inner hearing echoes previous distinctions such as the one between the *generative component* (i.e., the feeling of producing speech) and the *auditory component* (i.e., the feeling of hearing speech) of inner speech (e.g., MacKay, 1992) and the distinction between the *inner voice* and the *inner ear* in working memory (e.g., Baddeley et al., 1984; Buchsbaum & D'Esposito, 2019).

frontal cortex or the pre-supplementary motor area (Nalborczyk et al., 2022). The model put forward by Løevenbruck et al. (2018) predicts that the primary motor cortex will be involved during inner speaking, but it leaves unspecified the neural mechanisms supporting inner hearing and whether they differ from those supporting inner speaking.

According to the dual stream prediction model (Tian et al., 2016; Tian & Poeppel, 2013, 2012), the sensory content of inner speech is provided by two distinct processes. First, the sensory content of inner speech may result from a *motor simulation prediction stream*. In this view, inner speech would involve the same mechanisms as overt speech production except that the speech acts should be inhibited rather than executed (this proposal is similar to the model of Løevenbruck et al., 2018, although see below differences regarding the involvement of M1). Second, the sensory content of inner speech may be provided by an associative memory-based process called the *memory-retrieval prediction stream* (Kosslyn et al., 1979; Moulton & Kosslyn, 2009; Tian & Poeppel, 2012). In this view, sensory percepts are motor-to-sensory associations established during past events and directly retrieved from long-term memory.²

The distinction between the motor stimulation and memory retrieval streams has been linked to the distinction between inner speaking and inner hearing (e.g., Tian et al., 2018, 2016; Tian & Poeppel, 2013, 2012). Using fMRI, Tian et al. (2016) examined the neural correlates of articulation imagery (inner speaking) and hearing imagery (inner hearing) and observed that inner speaking more strongly recruits brain areas belonging to the motor-estimation stream whereas inner hearing more strongly recruits brain areas belonging to the memory-retrieval prediction stream. Moreover, these two imagery modes

² The distinction between these two prediction streams is reminiscent of the distinction between the prediction-by-simulation and the prediction-by-association mechanisms in speech production and perception (Pickering & Garrod, 2013) and was previously discussed in more depth in Li et al. (2020), Ma and Tian (2019), Nalborczyk (2019), Nalborczyk et al. (2021), Tian and Poeppel (2012), and Tian and Poeppel (2013).

have been shown to have distinct MEG correlates and distinct modulatory effects on a subsequent /ba/-/da/ auditory categorisation task (Ma & Tian, 2019).

Critically, in the dual stream prediction model, the primary motor cortex (M1) is considered to be “bypassed” when producing inner speech (Tian et al., 2016; Tian & Poeppel, 2013, 2012). In comparison, the model introduced in Lœvenbruck et al. (2018) and Grandchamp et al. (2019) predicts that the primary motor cortex is involved during inner speech production. In essence, at least some forms of inner speech may be accompanied by the emission of motor commands that are subsequently inhibited by cortical and subcortical mechanisms.

The hypothesis that inner speech involves motor inhibition is compatible with behavioural, lesional, and neuroimaging studies of motor imagery (for a review, see Guillot et al., 2012). The involvement of the primary motor cortex during inner speech and its partial inhibition by cortical and subcortical mechanisms may explain the residual peripheral muscular activity that is sometimes observed during inner speech production (Jeannerod, 2006; Lœvenbruck et al., 2018; Nalborczyk, 2019). Another example is the observation that inner speech is accompanied by an increase in tongue motor excitability, compared to rest or to an auditory speech perception condition (Maegherman et al., 2020). If the dual stream prediction model is correct in that the primary motor cortex is “bypassed” during inner speech, neither inner speaking nor inner hearing should increase the involvement of the primary motor cortex. In contrast, if the motor control view is correct in that the primary motor cortex is involved (but actively inhibited by cortical and subcortical mechanisms), inner speaking should be accompanied by an increase in motor cortex excitability.

Transcranial magnetic stimulation (TMS) has been used to probe the involvement of the motor system in speech production and perception (for a review, see Devlin & Watkins, 2007). Single TMS pulses can be applied to the primary motor cortex (M1) to elicit motor

evoked potentials (MEPs) in the orofacial muscles. MEPs can be recorded using surface
 electromyography (EMG). Their amplitude depends on the state of the motor system: it is
 greater during muscle contraction compared to rest. Therefore, MEP amplitude provides a
 direct measure of motor excitability that can be used to examine the involvement of the
 motor system during speech production and perception (Möttönen et al., 2014). For
 instance, seeing or hearing speech increases motor excitability in a content- and
 effector-specific manner, in the same way that observing hand movements does (e.g.,
 Fadiga et al., 2002; Watkins et al., 2003). Sub-cortically, however, MEPs recorded from the
 orofacial muscles and those recorded from the hand muscles originate from different motor
 pathways. Whereas muscles from the face are innervated by the corticobulbar pathway,
 muscles from the hand are innervated by the corticospinal pathway, with direct
 consequences on the shape and latency of MEPs. Indeed, MEPs recorded over the orofacial
 muscles peak around 10-15ms after the pulse, whereas MEPs recorded over the hand
 muscles peak around 20-25ms after the pulse, because (amongst other things) of the
 different lengths of the corticobulbar vs. corticospinal tracts (Adank et al., 2018;
 Maegherman et al., 2020; Möttönen et al., 2014).

We hypothesise that during inner speaking, sensory (e.g., auditory) percepts are
 mostly provided by a motor-to-sensory simulation, whereas during inner hearing, sensory
 percepts are mostly reconstructed from stored perceptual information. Therefore, inner
 speaking should be accompanied by an increase in motor cortex excitability evidenced by
 larger MEPs recorded over orofacial muscles. Conversely, inner hearing should be
 accompanied by a much reduced or even absent increase in motor cortex excitability
 (**hypothesis #1**). Our secondary hypothesis is that this increase in motor cortex
 excitability is content-specific, as it is usually observed in TMS studies of speech perception
 (e.g., Fadiga et al., 2002; Watkins et al., 2003). We predict that lip motor cortex
 excitability increases will be more pronounced when covertly speaking a syllable that
 should strongly recruit the lips (i.e., /bu/, hereafter referred to as a “rounded” syllable)

than when covertly speaking a syllable that should recruit the lips to a lesser extent (i.e., /gi/, hereafter referred to as a “spread” syllable) (**hypothesis #2**).

Methods

Ethics information

The present research complies with the French national ethics regulation (agreement ANSM 2017-A03614-49) and the Declaration of Helsinki. All participants will provide informed consent and receive a monetary compensation of 40€.

Design

The design is fully within participants, with two crossed two-level factors: inner speech mode (inner speaking vs. inner hearing) and articulatory features (rounded vs. spread syllables). The experiment also includes control trials during which single-pulse TMS will be applied to assess motor cortex excitability while participants are performing an unrelated task. In these control trials, participants will be asked to imagine tapping with their ipsilateral foot (i.e., to perform motor imagery of the foot; Figure 1).

Procedure

Transcranial magnetic stimulation. Participants will be familiarised with TMS before the training session. We will first ask the participants to fill out a safety screening form. Participants with contraindications for TMS (e.g., neurological disorders, medication, a family history of epilepsy) will not be included in the experiment. We will then explain the details of the experiment to the participant and obtain their written informed consent.

To ensure similar levels of muscle activation throughout the experiment, we will train the participants to maintain a baseline activity between 20 and 30% of their maximum voluntary contraction. To find the location of the motor lip representation on the contralateral primary motor cortex, we will follow the protocol described in Möttönen et al.

Figure 1. A. Experimental procedure. The main experimental part (post-training) involves 5 blocks of 40 trials each. aMT: active motor threshold, IS: inner speaking, IH: inner hearing. *B.* Illustrated timecourse of a single trial.

(2014) We will first localise the motor hand representation with the hotspot method, that is, by looking for the cortical site that elicits the maximal MEPs at a given intensity. Then, we will localise the lip hotspot from the hand one, by keeping a minimal 5-sec break between TMS pulses.

The active motor threshold will be defined as the minimal intensity necessary to elicit a lip MEP with a minimum peak-to-peak amplitude of approximately $50\mu\text{V}$ (as in Watkins et al., 2003; Watkins & Paus, 2004) in five stimulations out of ten (Rothwell et al., 1999). The intensity of the stimulator will then be set to approximately 120% of the active motor threshold (aMT) during the experimental session (this threshold may be slightly adjusted by participant). As in Maegherman et al. (2020), we will use a figure-of-eight coil placed around a 45° angle relative to the sagittal plane, inducing a posterior-to-anterior current

flow, approximately perpendicular to the lateral fissure. The position of the TMS coil relative to cortex will be continuously tracked and maintained throughout the experiment using a neuronavigation system. A standard MRI image will be used for the neuronavigation when the participant's MRI is not available. All TMS pulses will be monophasic and generated by a Magstim 200 device. We will report the average active motor threshold (expressed as a percentage of maximum stimulator output) for stimulation of the lip area, and its range.

Surface electromyography. EMG activity of the (right section of the) orbicularis oris (OO) muscle and the abductor pollicis brevis (APB) muscle of the right hand will be recorded bipolarly with surface electrodes connected to a 16-channel amplifier (BrainAmp ExG with eight bipolar and eight auxiliary channels, Brain Products Company, Gilching, Germany) at a sampling rate of 5kHz. The EMG signal will then be band-pass filtered between 20 and 450Hz, following standard guidelines for surface facial EMG (De Luca et al., 2010). We will then compute the area-under-the-curve (AUC) of the rectified EMG signal. The covered area will be taken as an index of the MEP size (Maegherman et al., 2020). In each trial, the MEP AUC will be computed in a window spanning from 8 to 35ms after the TMS pulse. As in Maegherman et al. (2020), a pre-pulse section of 27ms (i.e., from 35 to 8ms before the pulse) will be extracted to allow a posteriori checks of equivalent baseline contraction across conditions.

Using alcohol, we will clean the skin on the right section of the OO, above the belly of the APB muscle, as well as the skin around the site of the ground electrode placed on the right temple. We will then attach electrodes on these sites. We will visually check the recorded EMG signals. If the signals appear to be noisy, we will re-clean the skin and re-attach the electrodes. We will then proceed with the localisation of the motor hand representation as described in Möttönen et al. (2014), from which we will localise the “hot spot” for the motor lip representation. Then, we will determine the aMT for each participant, as described previously.

Training blocks. Training will be composed of two blocks. In the first block, participants will be trained to either produce (overtly) or to listen to a syllable for a 2-sec period at a 2.5Hz pace (20 hearing and 20 speaking trials; Figure 1). First, a syllable will be presented on screen for 1 sec. In speaking trials, participants will then have to repeatedly utter this syllable at 2.5Hz for 2 sec. The 2.5Hz pace will be cued by the display of a green cross on the screen. In hearing trials, participants will be asked to listen to recordings of two native French speakers uttering the target syllables at a 2.5Hz pace. The syllables were chosen to induce a stronger involvement of the orbicularis oris muscle or of the zygomaticus muscle (i.e., /bu/ vs. /gi/, respectively). At the end of this first training block, participants will be given earplugs to reduce the discomfort caused by the TMS click sound (Counter et al., 1991).

In the second training block, participants will be familiarised with the phenomenological contrast between inner speaking and inner hearing conditions. In the inner speaking conditions, participants will be asked to imagine speaking the syllables “in their mind” without moving the speech effector and without producing any sound (as in Tian et al., 2016). In the inner hearing conditions, participants will be asked to recreate in their minds the voice from the hearing trials used in the first training block, while also minimising the feeling of movement in their speech effectors (as in Tian et al., 2016).

It should be noted that Tian and Poeppel (2012), Tian and Poeppel (2013), and Tian et al. (2016) use different definitions of inner speaking and inner hearing than Hurlburt et al. (2013). For the former, inner speaking refers to the act of silently (mentally) talking to ourselves from the first perspective, with our own perceived voice, whereas inner hearing refers to the act of imagining hearing speech, produced with the voice of someone else (sometimes designed as auditory verbal imagery). When defined in these terms, the distinction between inner speaking and inner hearing may be considered as the “speech analogue” of the distinction between first-person and third-person motor imagery in the

motor imagery literature. As noted by Alderson-Day and Fernyhough (2015) however, this operationnalisation of the phenomena of inner speaking and inner hearing make it difficult to distinguish between the influence of the perspective and the distinction between inner speaking and inner hearing per se.

Main procedure. The timing of trials will be identical across conditions (Figure 1). In each trial, the target syllable (i.e., /bu/ vs. /gi/, displayed as “bou” vs. “gui”), together with a pictogram indicating whether the participant should generate inner speaking, inner hearing, or to relax, will be displayed for 2000ms. We will use a pictogram that does not directly refer to the effector targeted by the TMS pulse to avoid automatic activation of the corresponding effector (see Figure 1). Then, a green cross will appear at the center of the screen every 400ms (i.e., at a 2.5Hz pace) for 3.2sec. Participants will be instructed to start producing the syllable at the apparition of the first green cross, and to keep repeating it in rhythm with the apparition of the green cross (i.e., every 400ms). In all three task conditions, the TMS pulse will exactly occur either on the fourth, fifth, sixth, or seventh green cross. We decided to vary the occurrence of the TMS pulse to maintain the participant’s attention on the task throughout the experiment and to reduce the predictability of the pulse’s occurrence. At the end of each trial, the last (i.e., eighth) green cross will be followed by a blank screen presented for 1000ms. This procedure will result in inter-pulse-intervals varying between 5000ms and 7400ms.

The main experimental part (post-training) will consist of five blocks of 40 trials each, resulting in a total of 200 trials/MEPs per participant (40 control trials, 80 inner speaking trials: 40 /bu/ and 40 /gi/, and 80 inner hearing trials: 40 /bu/ and 40 /gi/). The order of trials within each experimental block will be randomised across participants. Each block will be followed by a 1min resting period. Finally, we will ask the participants to fill out the Movement Imagery Questionnaire-3 Second French version (Robin et al., 2020). The experimental procedure will be developed using the PsychoPy software (Peirce et al., 2019). Participants will be then fully informed about the theoretical rationale for the study and

compensated for their participation.

Sampling plan

We will recruit students or staff members from Aix-Marseille Université between 18 and 35 years old, with no history of psychiatric or neurological disorder, speech disorder, or hearing deficit. Participants will be recruited through university mailing lists.

To define the number of participants, we conducted a Bayesian a priori power analysis, where “statistical power” is to be understood in its general meaning, that is, the probability of achieving some statistical goal (Kruschke, 2015). We simulated data (see the supplementary materials for more details) by varying the number of participants (from 20 to 50) and the number of trials in each condition (30 vs. 60). We were interested in the probability of detecting two effects: i) the main effect of the inner speech mode, that is, the difference between the average MEPs in the inner speaking vs. inner hearing conditions (60 trials in each condition), and ii) the effect of the type of syllable, that is, the difference between the average MEPs for /bu/ vs. /gi/ trials *within* the inner speaking condition (30 trials in each condition).

The null hypothesis (i.e., no difference between conditions) requires more observations to be corroborated than the alternative hypotheses of small, medium, or large effects (e.g., Schönbrodt et al., 2017; Schönbrodt & Wagenmakers, 2018). Therefore, we decided to plan for a null effect to obtain a conservative estimate of the number of observations and participants needed to detect all sorts of effects, from null to large. This analysis revealed that, with 30 or more observations per participant and per condition, we need at least 30 participants to reach a probability equal or superior to 0.9 of obtaining a BF equal or superior to 10 in favour of the null hypothesis. The detailed resulting power curve and the reproducible code used to conduct this analysis are available in the online supplementary materials.

Analysis plan

All analyses will be conducted in R (R Core Team, 2021). We will fit Bayesian multilevel models using the `brms` package (Bürkner, 2017) with two categorical predictors (recoded using sum contrasts as -0.5 vs. 0.5): the inner speech mode (i.e., inner speaking vs. inner hearing), the type of linguistic item (i.e., /bu/ vs. /gi/), and the AUC of the lip MEP as a continuous dependent variable (for an introduction to Bayesian multilevel modelling, see Nalborczyk et al., 2019). For each effect of interest, we will report the mean of the posterior distribution along with its 95% credible interval, as well as the mean of the posterior distribution of the standardised mean difference (Cohen's *d*) with its 95% credible interval, when appropriate (i.e., when comparing two conditions). We will also report the Bayes factor (BF), which quantifies the relative support (evidence) for either the null or the alternative hypothesis (e.g., Wagenmakers, 2007). Data collection and analysis will not be performed blind to the conditions of the experiments.

We will test for differences in baseline background contraction across conditions per participant. If this test reveals a difference (i.e., a $BF_{10} > 10$), we will apply the common range correction (as in Spieser et al., 2013; method adapted from Schieppati et al., 1996). This method consists in removing trials below the maximum value of minimum values across conditions and trials above the minimum value of maximum values across conditions, per participant. After removing these trials, we will then test again for a difference. If there still is a difference across conditions, we will remove this participant from the subsequent analyses. If there is no difference across conditions, and if there are at least 20 trials per condition left for this participant, we will keep it in the subsequent analyses. If the common range procedure removes more than 20 trials per condition and participant, we will apply another procedure in which all trials are kept, consisting in including the background contraction level as a continuous predictor in the statistical models.

The first MEP in each block will be removed as it is usually much larger than those

292 that follow. As noted by Möttönen et al. (2014), it is not always possible to record robust
293 lip MEP when the lips are “relaxed”. Therefore, we will report the number of participants
294 in which the experiment could not be carried out (i.e., participants for which the
295 stimulation was uncomfortable and participants in which we could not elicit MEPs).

Data availability

All data will be made freely available through Github and the Open Science Framework: <https://osf.io/7kwv6/>.

Code availability

All experimental material and analyses scripts will be made freely available through Github and the Open Science Framework: <https://osf.io/7kwv6/>.

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Author contributions

Conceptualisation: LN, ML, LS, FXA; Data curation: LN, LS, VS; Formal analysis: LN, LS; Funding acquisition: LN, ML, LS, FXA; Investigation: LN, LS; Methodology: LN, ML, MB, VS, LS, FXA; Project administration: LN, ML, MB, LS, FXA; Resources: LN, ML, MB, LS, FXA; Software: LN, LS, VS; Supervision: ML, MB, LS, FXA; Validation: ML, FXA; Visualisation: LN; Writing - original draft: LN; Writing - review and editing: LN, ML, MB, LS, FXA.

Competing interests

The authors declare no competing interests.

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Table 1. Design table

Question	Hypothesis	Sampling plan	Analysis plan	Interpretation given to different outcomes
Does inner speaking induce a stronger increase in motor cortex excitability than inner hearing?	Hyp1: Inner speaking will be associated with larger MEPs (i.e., higher AUCs) than inner hearing.	We determined the sample size based on an a priori power analysis (cf. main text).	The outcome is the mean AUC, computed from the rectified MEP. We will fit a Bayesian multilevel linear regression model with inner speech mode as a binary predictor.	Bayes factors will be interpreted in a continuous way. However, to facilitate interpretation, the results will also be considered consistent with the hypothesis if $BF_{10} > 3$. The results will be considered consistent with the null hypothesis if $BF_{10} < 1/3$.
Is this increase specific to the content produced in inner speaking?	Hyp2: The inner production of the /bu/ syllable will be associated with larger MEPs than the inner production of the /gi/ syllable in the inner speaking condition.	Same as above.	The outcome is the mean AUC, computed from the rectified MEP. We will fit a Bayesian multilevel linear regression model with inner speech mode and the linguistic material as binary predictors. We will then inspect the difference between /bu/ and /gi/ syllables within the inner speaking condition.	Same as above.

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