TMS uncovers details about sub-regional language-specific processing networks in early bilinguals

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ARTICLE INFO

ABSTRACT

Despite numerous functional neuroimaging and intraoperative electrical cortical mapping studies aimed at investigating the cortical organisation of native (L1) and second (L2) language processing, the neural underpinnings of bilingualism remain elusive. We investigated whether the neural network engaged in speech production over the bilateral posterior inferior frontal gyrus (pIFG) is the same (i.e., shared) or different (i.e., language-specific) for the two languages of bilingual speakers. Navigated transcranial magnetic stimulation (TMS) was applied over the left and right posterior inferior gyrus (pIFG), while early simultaneous bilinguals performed a picture naming task with their native languages. An ex-Gaussian distribution was fitted to the naming latencies and the resulting parameters were compared between languages and across stimulation conditions. The results showed that although the naming performance in general was highly comparable between the languages, TMS produced a language-specific effect when the pulses were delivered to the left pIFG at 200 ms poststimulus. We argue that this result causally demonstrates, for the first time, that even within common language-processing areas, there are distinct language-specific neural populations for the different languages in early simultaneous bilinguals.

Introduction

What is the exact functional neuroanatomy underlying bilingual speech production? Are there functionally separate language-specific neural populations dedicated for native (L1) and second (L2) language production or is there a single shared neural network sustaining both languages? The majority of results from various functional neuroimaging studies suggest that L2 production relies on the same neural substrates involved in monolingual language processing (for reviews, see Abutalebi et al., 2001; Abutalebi and Green, 2007). Such neural convergence (Abutalebi and Green, 2007; Green, 2003) seems to hold particularly true for bilinguals who have acquired both their languages from early on in life (Bloch et al., 2009; Hernandez et al., 2001; Kim et al., 1997) or who

are otherwise highly proficient in their L2 (Chee et al., 1999; Consonni et al., 2013; Klein et al., 1995, 1994). With lower levels of proficiency, however, brain activations in response to L2 production have been shown to be more extensive and more varied (Bloch et al., 2009; Kim et al., 1997) compared to the pattern of activations elicited by L1 production. Rather than being interpreted as evidence for language-specific processing, this difference has been attributed to the need for low-proficient bilinguals to recruit more extensive cognitive control mechanisms to aid the conscious and effortful L2 production (Abutalebi and Green, 2007). However, as more extensive L2 brain activations have also been observed for high-proficient early bilinguals (Perani et al., 2003), the proficiency-related cognitive control processes alone might not be sufficient for explaining the difference in activations between L1 and L2.

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Indeed, an accumulating number of intraoperative electrical cortical mapping studies have challenged the neural convergence hypothesis by demonstrating that most bilinguals have both common and dedicated language-specific cortical areas for their two languages (for review, see Giussani et al., 2007). More recently, the same common-plus-distinct bilingual language processing configuration has also been recently reported using transcranial magnetic stimulation (TMS) (Tussis et al., 2017). Brain stimulation provides better causal certainty compared to correlative functional imaging studies (Weber and Thompson-Schill, 2010); it illuminates the necessary brain areas (Krings et al., 2001) instead of just participating areas related to a specific function, that is, provides causal instead of correlational information. As such, the findings that speech production in L1 and L2 can be selectively disrupted from several spatially distinct cortical locations (Fernández-Coello et al., 2016; Lucas et al., 2004; Ojemann and Whitaker, 1978; Roux et al., 2004; Roux and Trémoulet, 2002; Tussis et al., 2017; Walker et al., 2004) provide indisputable evidence for at least partially separate neural networks in sustaining multiple languages within the bilingual brain. Moreover, language-specific areas have been observed irrespective of the level of L2 proficiency and the age of L2 acquisition (AoA) (Fernández-Coello et al., 2016; Giussani et al., 2007; Tussis et al., 2017; Walker et al., 2004), suggesting that even when multiple languages have been acquired simultaneously in early childhood, a certain degree of neural separation of languages pertains. The findings have, however, been somewhat inconsistent in indicating which cortical regions are likely to exhibit spatial segregation of languages, leaving room for speculations about whether AoA and proficiency might still influence the anatomical distributions of common and separate language processing areas. Namely, while some studies have reported language-specific areas located almost exclusively in posterior and temporo-parietal cortices (Lucas et al., 2004; Tussis et al., 2017), others have discovered common and language-specific regions in both frontal and posterior temporal and parietal areas (Fernández-Coello et al., 2016; Giussani et al., 2007; Roux et al., 2004; Roux and Trémoulet, 2002; Walker et al., 2004).

Although the aforementioned evidence of spatial segregation of languages advocates for distinct L1 and L2 processing networks, it is not necessarily a prerequisite for language-specific neural networks to exist. In fact, it has been proposed that even when multiple languages appear to share neural resources at the same gross anatomical location (common language processing site), the different languages might be subserved by intricately interwoven yet distinct neural circuits (Paradis, 2009, 2004). Although unequivocal evidence endorsing distinct language-specific neural populations within the common language processing areas has not yet been provided, some functional imaging studies have suggested this by demonstrating that L1 and L2 processing activates roughly the same cortical regions with slightly differently distributed centres-of-activations (Kim et al., 1997; Marian et al., 2003; Xu et al., 2017). Thus, the neural separation of languages may not need to be confined to the language-specific cortical locations, but could be a more pervasive phenomenon present also in the common language processing sites.

Here, we investigated the bilingual language organisation over Broca's area and its right-hemispheric homologue during bilingual spoken word production. Our goal was to specifically examine whether the neural network engaged in speech production over the bilateral posterior inferior frontal gyrus (pIFG) differs for the two languages of a bilingual speaker. To this end, we applied event-related navigated TMS while early simultaneous bilinguals performed a picture naming task in their two native languages. Like intraoperative electric stimulation, TMS utilises exogenous electric fields to obstruct or perturb ongoing cortical activations. TMS has, however, an advantage over the electrical cortical stimulation, as it does not require an invasive craniotomy, but instead uses a pulsed electromagnetic induction to generate a transient electric field in the brain. Thus, TMS provides a unique wherewithal to directly probe the functional neuroanatomy of cognitive functions, such as language (Lioumis et al., 2012), in a controlled experimental setting with healthy volunteering participants.

A few competing hypotheses about the neural organisation of bilingualism can be formulated. Ideally, if a single shared neural network is used to process both languages in a similar manner, the neurodisruptive effect of TMS should be symmetric between languages, i.e., stimulation should induce comparable naming performance changes in both languages. In contrast, should TMS result in asymmetric performance between languages, it could signify that the stimulated neural networks sustaining L1 and L2 processing are language-specific. The behavioural effects of TMS have, however, been shown to depend on the activity state of the stimulated neural populations (Cattaneo et al., 2008; Perini et al., 2012; Silvanto and Pascual-Leone, 2008). Hence, TMS could provoke asymmetric performance even if both languages are reliant upon the same shared neural network, but the overall level of activation within that network differs between languages. As some of the neuroimaging studies reviewed above did, in fact, report differing activation levels for L1 and L2 during speech production tasks (e.g., Perani et al., 2003), TMS-induced asymmetry in performance *per se* does not guarantee that the two languages are processed with two distinct language-specific neural populations. However, since the neural impact of the stimulation does not depend solely on the properties of the given external stimulus but on the initial activity- or brain-state at the time of stimulation (Perini et al., 2012; Silvanto et al., 2007; Silvanto and Pascual-Leone, 2008), it stands to reason that each unique brain-state gives rise to a unique behavioural outcome. Specifically, the three neural architectures considered above, that is, 1) a shared network, no difference in activation levels between languages; 2) a shared network, differing activation levels between languages; and 3) distinct language-specific neural networks, should thus each be linked to a particular behavioural outcome.[1] Based on this, we hypothesise that should bilingual language production within the common language processing area rely on two distinct language-specific neural networks, L1 and L2 production should generate two *qualitatively* different brain-states due to activating different neural populations. As such, we hypothesise that TMS-induced asymmetric behavioural outcomes reflecting distinct language-specific neural networks are also qualitatively different between the languages. For instance, stimulation might evoke increased number of erroneous responses in one language, while affecting the mean response times in the other language. Conversely, if both languages use a shared neural network but with different activation levels, the brain-states can be expected to be *quantitatively* different between languages, reflecting the difference with which each language activates the same neural populations. In the same vein, the stimulation-induced asymmetric behavioural outcomes that reflect this kind of a shared-network-differing-activation-levels neural architecture can also be hypothesised to differ in quantity. For example, stimulation might affect only the mean response times for both languages, and the change should be more pronounced for one language compared to the other. These hypotheses are summarised in Table 1.

Whilst there are no prior studies that would have directly compared the behavioural outcomes related to stimulating *qualitatively* vs. *quantitatively* different neural networks, there is isolated evidence supporting the idea that TMS can, indeed, be used to distinguish between two physically distinct neural networks vs. two different activation levels within the same network. First, TMS has already been successfully used

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[1] Multiple languages could also be argued to be represented with language-specific dynamics within a shared neural network. However, this kind of a neural architecture, where all neurons are shared between the languages, but the activations are qualitatively different for each language, is rather unlikely. Evidence supporting the idea that the dynamics of L1 and L2 processing are highly comparable comes from the already mentioned functional imaging studies suggesting language-specific neural populations within common language processing areas (Kim et al., 1997; Marian et al., 2003; Xu et al., 2017), and from several electroencephalography findings showing that high-proficiency L2 processing produces native-like electrical responses (Dowens et al., 2010; Hahne et al., 2006; Tanner et al., 2009).

Table 1
Expected behavioural outcomes associated with each neural architecture.

	Level of activation between languages	
	Same	Different
Shared network	symmetric	asymmetric, quantitative
Language-specific networks	asymmetric, qualitative	

to selectively stimulate distinct sub-regional neuronal populations (Silvanto et al., 2007). Moreover, the results obtained support the assumption that TMS affects distinct sub-regional neural populations in a qualitatively different fashion. In their elegant study, Silvanto and colleagues (2007) stimulated the occipital cortex in order to induce illusory visual percepts known as phosphenes. Normally, such phosphenes are perceived as achromatic (white), presumably because the sub-regional colour-sensitive neural populations in the early visual cortex (Engel, 2005) are all equally susceptible to TMS (i.e., exhibit equal baseline activation levels). However, when specific colour-sensitive populations were made more susceptible to TMS by lowering the baseline activation level of those neurons via colour adaptation, the TMS-induced phosphenes assumed the colour of the adapting stimulus. That is, adapting to green caused the phosphenes to appear as green, and so on. Thus, these findings demonstrate that the quality of the TMS-induced outcome, the colour of the phosphene in this case, is directly dependent on the stimulated sub-regional population. Finally, further evidence supporting the theory that distinct neural representations produce qualitatively different outcomes when processing is disrupted comes from bilingual lesion studies. Considering that TMS-induced neurodisruptive effects have sometimes been referred to as "virtual lesions" (Pascual-Leone et al., 2000, 1999), lesion studies reporting selective patterns of impairment/recovery for the two languages of a bilingual speaker (e.g., Aladdin et al., 2008; García-Caballero et al., 2007; Gomez-Tortosa et al., 1995) suggest that TMS could evoke similar qualitatively different language-selective "impairments". For example, Gomez-Tortosa and colleagues (1995) described a patient with qualitatively different L1 and L2 deficits following a lesion surgery in the left perisylvian area; while the patient demonstrated only a mild naming deficit in her L2, she had paraphasias and a significantly more severe naming deficit in her L1.

Second, regarding *quantitative* differentiation between two different activation levels within the same neural network, there are systematic findings linking increased cortical activity level to enhanced TMS-evoked physiological outcomes. More specifically, TMS to the motor cortex induces peripheral muscle activity, which can be recorded with motor evoked potentials (MEPs). Enhanced MEP amplitudes have been found in response to stimulation delivered during (pre)movement vs. no movement (e.g., Chen et al., 1998; Rossini et al., 1988; Yamanaka et al., 2002). This demonstrates a direct relationship between quantitative increase in the cortical activity and quantitative increase in the TMS-induced response. Critically, in addition to modulating the MEP amplitudes, increased movement-related excitatory activity in the motor cortex has also been shown to lead to a systematic change in the amplitudes of the TMS-evoked event-related potentials recorded directly from the scalp by using concurrent electroencephalography (Nikulin et al., 2003); Because MEPs actually represent the sum of processes occurring at the cortical, subcortical, and spinal levels (Rossini et al., 1994), this EEG finding is important in demonstrating that quantitative TMS-evoked changes are, in fact, due to changes in cortical activity as opposed to, for instance, changes in spinal-cord processes.

Careful experimental design can further facilitate the interpretability of the TMS-effects. As it remains unclear whether the L2 AoA and/or proficiency might influence the neural organisation of languages, we chose to investigate highly balanced, early simultaneous bilinguals with two equally strong native tongues in order to maximise the comparability

across languages. Importantly, simultaneous bilinguals have been shown to differ from other kinds of bilinguals with respect to the degree of cognitive control processes engaged in producing L1 vs. L2 words. That is, using language switching tasks, several studies have suggested that bilingual speech production entails an inhibitory control process designed to suppress the neural representations of L1 words when L2 is being produced and vice versa (for review, see Declerck and Philipp, 2015). Since the dominant language (L1) is typically suppressed more strongly than the weaker language (L2) (e.g., Meuter and Allport, 1999; Macizo et al., 2012), the amount of suppression applied to each language is thought to be proportional to the level of activation of the language that needs to be suppressed (Green and Eckhardt, 1998). Critically, in early simultaneous bilinguals, the amount of assumed suppression does not vary between languages (see Calabria et al., 2011; Costa and Santesteban, 2006, 2004 for behavioural evidence, and Duñabeitia et al., 2010 for electrophysiological evidence), suggesting that both languages induce equal levels of neural activation during spoken word production. Consequently, it has been suggested that for these kinds of early simultaneous bilingual speakers, the terminological distinction between L1 and L2 languages is inappropriate, as they seem to have two equally strongly represented and controlled L1 languages (Duñabeitia et al., 2010; Perea et al., 2008). Nonetheless, these findings have important implications for the possible asymmetric TMS-induced effects for two reasons. First, recall that in Silvanto and colleagues' (2007) study, sub-regional stimulation was achieved by modifying the pre-TMS activation levels of the distinct neural populations within the stimulated region. If there are language-specific neural networks in the pIFG, it is unlikely that the neural network representing the non-target language would be fully "switched off" during target language production (e.g., Kroll et al., 2006). Rather, the above-discussed inhibitory control process most likely suppresses the activity level of the non-target language network relative to target language network. This relative suppression creates a pre-TMS baseline activity level difference between the two postulated sub-regional populations, similar to the between-population activation level difference achieved via colour adaptation in Silvanto et al. (2007) study. Crucially, as suggested by the observed symmetrical switching costs, this suppression is balanced between languages, akin to colour-adaptation being balanced for each colour (i.e., there is no reason to expect that adapting to green might cause a more intense adaptation effect than, for instance, adapting to red). Without this balance, it would be difficult to interpret which TMS-induced effects might reflect differences in suppressing language-specific populations and which might be due to the shared-network-differing-activation-levels neural architecture. The other important implication that can be drawn from the symmetric switching findings is that since they imply equal activation levels for L1 and L2, the shared-network-differing-activation-levels interpretation is rendered less likely.

To further account for the possibility that different levels of activation might result in asymmetric TMS effects, we included both high- and low-frequency linguistic stimuli. The rationale was based on the idea that high-frequency words have higher levels of baseline activation than low-frequency words (Kroll and Gollan, 2013) and this difference is reflected directly in the intensity with which high- and low-frequency words activate the language-related brain regions during speech production (Carreiras et al., 2006; Strijkers et al., 2010). Thus, should TMS induce asymmetric changes between languages in an absence of similar changes between high- and low-frequency words, the effect is likely to reflect language-specific neural basis for the two languages. On the other hand, a shared neural network is indicated if the changes are asymmetric but similar across languages and different frequencies.

With respect to the stimulation location, the selection of Broca's area was motivated by several factors. First, the left pIFG is one of the core cortical regions taking part in language production process (for reviews, see Indefrey and Levelt, 2004; Indefrey, 2011) and thus a likely epicentre for bilingual language processing, that is, a site where both languages share the same coarse location (Fernández-Coello et al., 2016; Lucas et

al., 2004; Tussis et al., 2017). Second, the temporal characteristics of neural activations over the left IFG during overt speech production are already well-established: based on an extensive meta-analysis of 58 neuroimaging studies of (monolingual) word production, Indefrey and Levelt (2004) proposed that Broca's area dominantly contributes to the production process at around 300–400 ms after speech production initiation. Crucially, the few existing TMS studies investigating the time-course of functional activation in Broca's area have shown that stimulation over the pIFG has a time-specific effect on (monolingual) picture naming, causing naming latencies to become delayed only when pulses are delivered at around 225–300 ms after the onset of picture presentation (Schuhmann et al., 2012, 2009; Wheat et al., 2013). The final factor relates to this time-window of functional activation. Bilinguals are, in general, slower to produce names for objects in their (weaker) L2 vs. L1 (for overview, see Hanulová et al., 2011). Although it remains debatable at which exact processing stage the L2 production starts to become delayed relative to the L1 production, an emerging consensus posits that the delay does not arise before lexical selection (Hanulová et al., 2011) and possibly even the retrieval of the word initial phonemes (Hanulová et al., 2008 in Hanulová et al., 2011) has been completed. However, due to the paucity of studies investigating the exact temporal characteristics of L1 and L2 production process, it remains unknown where the divergence point lies time-wise. One of the few reference points comes from an electroencephalography study conducted by Christoffels et al. (2007); they showed that for the first 400 ms, the event-related potentials elicited by L1 and L2 picture naming task were identical. Since the production-related functional activations at Broca's areas are expected to take place before 400 ms (at around 300–400 ms), it rules out the likelihood that any emerging TMS-induced effects might be due to differences in temporal characteristics between processing of different languages.

To summarise, we aimed to investigate the bilingual neural organisation of languages within a single common language processing area. Navigated TMS was used to systematically modulate the functional activations over the bilateral pIFG while bilinguals performed a picture naming task with their two native languages. Building on the state-dependency of TMS, we hypothesised that different neural architectures should interact uniquely with the stimulation, thus producing also unique behavioural outcomes, listed in Table 1. Careful experimental design was used to minimise any confounding factors such as potential between-languages differences related to the time-course of the word production process.

Methods

Participants

15 young right-handed adults (4 males, mean age 23.73 years, SD = 3.13 years) participated in the study.[2] All participants were native Finnish–Swedish speakers, who had learned both their languages before the age of 5 (mean L2 AoA = 2.20, SD = 1.82). They reported very high proficiency and daily usage of both languages. Participants' detailed language backgrounds are presented in Table 2. Participants reported no neurological or psychiatric disorders nor had they medications that might affect the central nervous system. The participants gave their written informed consent to participate in the experiments. The experiments were performed in accordance with the Declaration of Helsinki. The University of Helsinki Ethical Review Board in the Humanities and Social and Behavioural Sciences issued ethical permission for the experiment.

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[2] Three more participants (all males) volunteered to participate in the study. They were not, however, included in the analysis, as two wished to discontinue the TMS measurement after preparations due to anxiety caused by the measurement and one had started a medication for clinical depression after the initial MRI scan (a contraindication for TMS).

Table 2
Participants' language background.

Languages in childhood	% of participants	
Both languages at home	73.33	
FIN at home, SWE outside home	26.67	
Schooling language	% of participants (FIN/ SWE)	
Primary school	-/100	
Upper comprehensive school	6.7/93.3	
Upper secondary school	6.7/93.4	
Language usage	Finnish (SD)	Swedish (SD)
% of all communications	42.67 (14.38)	36.67 (11.75)
% of speaking	48.00 (16.56)	44.67 (14.07)
% of reading	36.67 (17.99)	33.33 (17.18)
% of listening	41.33 (14.57)	36.00 (11.83)
% of writing	32.67 (17.51)	48.67 (21.33) **
Average language skills on scale from 1 (Beginner) to 7 (Excellent)		
Overall	6.87 (0.35)	6.93 (0.26)
Speaking	6.87 (0.35)	6.93 (0.26)
Reading	6.93 (0.26)	6.93 (0.26)
Listening	6.93 (0.26)	7.00 (0.00)
Writing	6.71 (0.47)	6.80 (0.41)
Languages at home	% of participants	
Only Finnish	40.00	
Only Swedish	6.67	
Both	53.33	
Languages at work	% of participants	
Only Finnish	26.67	
Only Swedish	20.00	
Finnish and Swedish	6.67	
Finnish, Swedish and English	46.67	
Languages at social situations	% of participants	
Finnish and Swedish	53.33	
Finnish, Swedish and English	46.67	

**p<.01.

MRI acquisition, diffusion data processing and tractography

Prior to the TMS experiment, the participants were scanned with Siemens Skyra 3T MR (Siemens PLC, Erlangen, Germany) scanner using a 32-channel head matrix coil. High-resolution anatomical images for each participant were obtained with a standard magnetisation-prepared rapid acquisition gradient echo (MPRAGE) sequence with the following parameters: repetition time (TR) 2530 ms, echo time (TE) 3.3 ms, inversion time (TI) 1100 ms, field-of-view 256 mm, voxel size $1 \times 1 \times 1$ mm^3, flip angle 7° and number of averages 1.

To maximise the effectiveness of the stimulation, we used individual diffusion tensor (DT) based deterministic tractography masks to more uniformly localise the individual stimulation targets across participants. Since we wished to target specifically the posterior part of the Broca's area associated with syllabification and other phonological word-form processes, we used the *arcuate fasciculus* (AF) to aid the target localisation. This approach was motivated by prior studies showing that, in general, functional language-related activations over Broca's area overlap closely with the AF (Powell et al., 2006; Propper et al., 2010). We assumed that the site where the direct segment of the AF originates from must be close to the hotspot for phonological word-form processing, because the direct segment has been proposed to support phonological language functions (Catani et al., 2005; Forkel et al., 2014; López-Barroso et al., 2013). Thus, the tractography-guidance was expected to provide some protection against the possibility that for some participants, the stimulation would have been less effective due to targeting an area away from the hotspot for phonological processing. For DT estimation, full

brain single-shot echo-planar imaging (SS-EPI) sequence was used (TR 9600 ms, TE 81 ms, field-of-view 240 mm, voxel size $2 \times 2 \times 2$ mm^3, b-value 1000 s/mm^2, number of averages 1, and GRAPPA factor 2). Our diffusion gradient scheme was provided by the vendor and consisted of diffusion-weighted volumes in 64 non-collinear directions with one b0-volume. To enhance the reliability of the DT estimations, additional two b0-volumes were gathered in both posterior-anterior and anterior-posterior phase encoding directions.

Diffusion weighted images were preprocessed using *topup* and *eddy* functions as implemented in FSL 5.0.8 (Andersson et al., 2003; Smith et al., 2004) installed on the Alcyone computing cluster at the University of Helsinki Department of Physics. Tensor estimations along with deterministic tractography were done using ExploreDTI (Leemans et al., 2009). Regions of interests (ROIs) for tractography were manually drawn based on anatomical landmarks to tract the left AF (Catani et al., 2002). Any anatomically implausible AF tracts originating from the ROIs, such as transcallosal tracts, were excluded with NOT ROIs. Final parameters for deterministic tractography that produced robust results for all participants were: minimum FA in seed point 0.2 and in tracing 0.1, maximum FA in tracing 1, maximum angle 55°, step size 0.5 mm, minimum and maximum tract lengths of 35 mm and 350 mm, and seedpoint supersampling $2 \times 2 \times 2$.

Visual stimuli

The stimuli consisted of two distinct sets of 60 colour pictures, one set for Finnish and the other for Swedish. Half of the pictures represented common everyday words (high lexical frequency words) such as *leipä* ('bread') or *koira* ('dog'), the other half featured less common words (low lexical frequency words) like *ankkuri* ('anchor') or *hyrrä* ('spinning top'). All the words were monomorphemic. The stimuli were meticulously matched across languages. A computerised search program WordMill (Laine and Virtanen, 1999) was used to obtain the lemma and surface frequencies of the target words of both languages. The Finnish words were retrieved from the unpublished Turun Sanomat (Finnish newspaper) lexical database with 22.7 million word tokens and the Swedish words from the unpublished Göteborgs–Posten (Swedish newspaper) lexical database, consisting of 24.2 million word tokens. Average lemma frequency was 2.77 per million (SD = 0.39) for high-frequency words and 1.81 per million (SD = 0.44) for low-frequency words. Average surface frequencies were 2.26 per million (SD = 0.32) and 1.27 per million (SD = 0.44) for high- and low-frequency words, respectively. The average length of the target words was 5 letters (SD = 1.02) and 4.6 phonemes (SD = 1.04). The length of the target words (whether in letters or in phonemes) did not differ between languages nor between frequencies. Mean phoneme lengths were 4.57 (SD = 0.94) for Finnish high-frequency targets, 4.80 (SD = 0.96) for Finnish low-frequency targets, 4.50 (SD = 1.28) for Swedish high-frequency targets, and 4.60 (SD = 1.00) for Swedish low-frequency targets. Phoneme length for individual target words was counted using the IPA phonetic notation. Representative pictures of the target word objects were acquired from a stock photo site (Shutterstock, 2014) and mounted on white background for presentation.

Paradigm and procedure

The stimuli were presented on a computer screen in front of the participant with a viewing distance of 60 cm. Stimulus presentation was governed by Presentation 14.4 software (Neurobehavioral Systems, Albany, NY, USA). Participants were asked to name the pictures out loud as rapidly as possible and to avoid verbal searching. Responses were recorded with an AKG C1000 S microphone (sampling rate 44.1 kHz 16 bit) placed nearby and digitised with a Focusrite Scarlett 2i2 USB-soundcard.

The TMS experiment consisted of two consecutive sessions, one for each language. Session order was counterbalanced across participants. Prior to each session, three practise blocks were presented to familiarise the participant with the pictures. The first experimental block in a session was a baseline measurement, where participants' naming latencies were recorded without TMS. After the baseline measurement, six conditions of TMS followed (see TMS parameters and sites), each condition in a separate block. The order of the TMS blocks was pseudorandomised across participants with a reduced Latin square. To account for any residual learning effects or carry-over effects from the stimulation, each session ended with a second baseline measurement without TMS. For analysis purposes, the distributions of baseline naming latencies obtained before and after the TMS conditions were collapsed to form an average distribution of baseline naming latencies. One session thus had 11 blocks in total. After the first session, there was a short break of approximately 5–10 min before proceeding to the second session.

The set of 60 pictures comprised a block. A trial began with a 500 ms presentation of a fixation cross, followed by a target picture, visible for 700 ms. 1300 ms of blank screen ended a trial. Picture order was randomised for each block. Each block lasted for 2.5 min, amounting for a total active measurement time of about 55 min. The experimental paradigm is shown in Fig. 1.

Only Finnish was used in communicating with the participants during the experimental situation. While this forced the participants to shift from a Finnish mindset to a Swedish mindset at the beginning of each Swedish block, the use of only Finnish was motivated by recent studies suggesting that language processing speed in early bilinguals can be affected by unexpected changes in established interlocutor–language associations (i.e., interlocutor suddenly speaking in a language not associated with his/her) (Martin et al., 2016; Molnar et al., 2015).
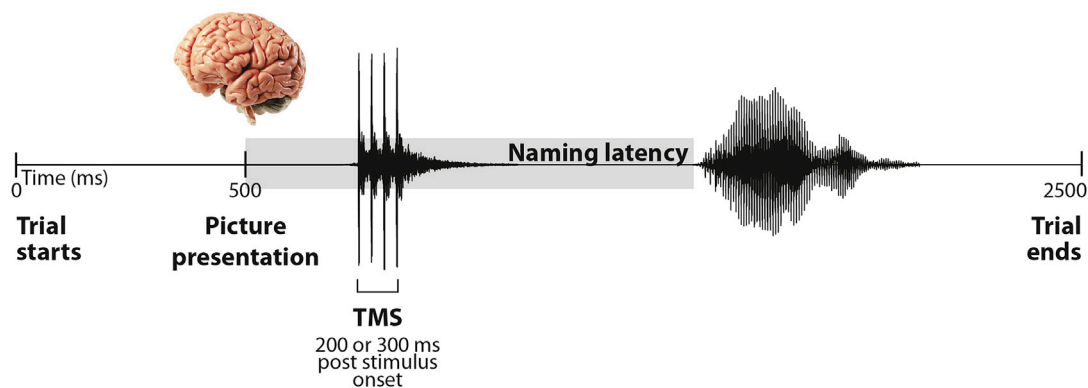
Fig. 1. Experimental paradigm, presentation of a trial. Preceding the stimulus presentation there was a fixation cross visible for 500 ms. The stimulus was visible for 700 ms. TMS pulses were locked to the onset of the stimulus presentation, occurring either 200 or 300 ms post stimulus onset depending on the condition. Naming latency was defined to be the time between the stimulus onset and the onset of naming (highlighted in the figure with grey background).

TMS parameters and sites

Short bursts of 40-Hz biphasic quadruple pulses were applied using the Nexstim NBS 4 navigated TMS device and a standard focal figure-of-eight coil (Nexstim PLC, Helsinki, Finland), which was held manually by the operator. The system provides real-time estimates of the direction, strength, and location of the maximum of the induced electric field on the visualised cortical surface, allowing accurate cortical targeting and monitoring of the TMS stimulation (Ruohonen and Karhu, 2010). Prior to the main experiment, the individual resting motor threshold (MT) of the right abductor pollicis brevis (APB) muscle was determined for each participant (Lioumis et al., 2012; Pascual-Leone et al., 1993). The electric field strength corresponding to the individual MT was used as the intensity for all TMS stimulation blocks.

The six TMS conditions comprised three stimulation sites with two different pulse timings. The main target site was the posterior part of the Broca's area in the frontal lobe of the left hemisphere, corresponding to the left pars opercularis. Additionally, stimulation was delivered to the Broca's anatomical homologue in the right hemisphere and to an active control site near the vertex (as opposed to sham stimulation, which does not produce the same skin sensation experienced when receiving active TMS stimulation, Jung et al., 2016). The exact stimulation sites over the temporal areas were chosen for each participant by overlaying an individual white matter tract mask of the left AF on a 3D reconstruction of the participant's brain. The target site on the left was selected to be in the near vicinity of the tracts originating from the pIFG. The right-hemispheric Broca's homologue was then defined to be the symmetrical site on the right pIFG. In the control condition, the stimulation location was aligned with the target sites in the anterior-to-posterior dimension and stimulation was delivered on the nearest gyral edge, just left to the vertex.

For each location, pulses were given 200 and 300 ms after the onset of the picture presentation. Pulse timing was motivated by previous literature indicating functional activation at Broca's area around 250–300 ms poststimulus presentation (Flinker et al., 2015; Schuhmann et al., 2012, 2009; Wheat et al., 2013). Pulse triggering was linked to the same Presentation software governing the presentation of the stimuli. From now on, TMS conditions are referred to with abbreviations per stimulation location and pulse timing: L200 and L300 refer to stimulation over the left pIFG 200 and 300 ms post stimulus onset, respectively; R200 and R300 refer to stimulation over the right pIFG 200 and 300 ms post stimulus onset, respectively; C200 and C300 refer to stimulation over the vertex control site 200 and 300 ms post stimulus onset, respectively. The condition where no TMS stimulation was applied is referred to as baseline (or, BL in Figures and Tables).

Preprocessing and statistical analysis

Naming latency recordings were filtered in Adobe Audition CC 2015 (Adobe Systems Inc., San Jose, California, U.S.) by using noise capture prints. The onset of naming was defined manually by selecting the time point where the amplitude of the digitised speech-wave detectably deviated from zero. The naming latency was determined as the time from the onset of the picture presentation till the onset of naming (Fig. 1). All responses were checked offline for semantic errors (wrong word), hesitations and phonetic errors; only correct and fluent responses were included to the analysis. Correct responses with audible verbal searching sounds preceding the naming were also discarded. In total, only 2.5% of all trials were excluded. Based on visual inspection, the excluded trials were randomly distributed across both languages and all conditions. Due to the small number of excluded trials, the naming accuracy was not analysed further.

To summarise, the data obtained comprised naming latencies on three levels of repeated effects (Language, Condition, Frequency) for
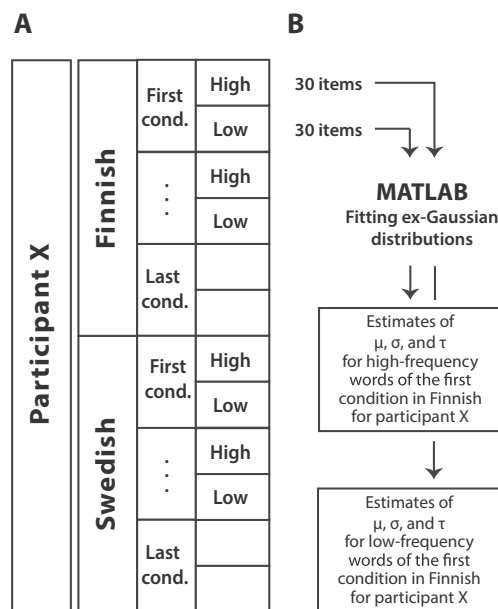

Fig. 2. A) Levels of the repeated effects. **B)** The ex-Gaussian distribution was fitted separately to the obtained distribution of naming latencies on each level of the repeated effects.

each participant (Fig. 2 A). Instead of analysing the data in terms of central tendency, that is, by looking at the mean and standard deviation (SD), we implemented an ex-Gaussian approach, as it provides a more detailed level of analysis by also accounting for the degree of the positive skew typical for response time (RT) data (e.g., Ratcliff and Murdock, 1976; Balota and Yap, 2011). The positive skew, i.e., the tail of the distribution, reflects the occasional extremely slow responses amidst otherwise relatively normally distributed responses. In analyses of central tendency, these extremely delayed observations tend to introduce disproportionately increased variance to the comparison, thus diminishing the statistical power of the analysis (Whelan, 2008; Wilcox, 1998). For this reason, many studies clip the outliers from the RT data or perform a logarithmic LN transformation to force the distribution to normal. The ex-Gaussian approach, on the other hand, treats the RT data as a convolution of a Gaussian and an exponential distribution to more accurately describe the shape of the RT distribution. Three parameters are used to separately characterise the location and the dispersion of the main body of the distribution (parameters μ and σ, representing the mean and SD respectively) and the size of the tail (parameter τ, representing the degree of the positive skew). Thus, we expected TMS-induced delay in the naming latencies to be reflected mainly as changes in the parameter μ. The parameter τ, however, has an important role in revealing whether TMS affects all targets relatively equally (motivating the clipping of outliers, reflected as changes only in the parameter μ) or if the extremely delayed trials might, in fact, represent relevant TMS-induced changes (i.e., changes in the parameter τ). In general, the ex-Gaussian approach has been shown to fit empirical RT data well (Balota and Spieler, 1999; Luce, 1986) and it has been widely used to analyse a variety of RT-based experiments (Henríquez-Henríquez et al., 2015; McAuley et al., 2006; Vaurio et al., 2009).

Estimates of the parameters μ, σ, and τ were obtained by fitting an ex-Gaussian distribution separately to the distribution of naming latencies at each level of the repeated effects within a subject (Fig. 2 B). The fitting was performed with the MATLAB (Mathworks, USA) toolbox "DISTRIB" (Lacouture and Cousineau, 2008), which utilises an iterative search based on maximum likelihood criteria to produce the parameter estimates that best fit the given naming latency distribution. To test the influence of the TMS on the ex-Gaussian distributional

measures of the naming latencies, a linear mixed model approach for repeated measures analysis of variance (rANOVA) was used with participants as random intercepts. Pairwise post-hoc tests were adjusted for multiple comparisons by using Bonferroni correction. In the model, μ, σ, and τ were treated as dependent variables (separate analysis for each parameter), while Language (Finnish vs. Swedish), Condition and Frequency (high-frequency words vs. low-frequency words) were defined as repeated factors. Regarding the Condition, two different analyses were performed. In the primary analysis, the no-TMS baseline condition was included as a control to all TMS conditions (Condition: BL, C200, C300, L200, L300, R200 and R300). This was done in order to evaluate a) whether stimulation over the fronto-temporal targets affected the naming performance at all and b) whether the presence or absence of the TMS pulse itself affects the participants' performance. The expectation was that stimulation over the target sites should be characterised with marked delays to the average naming performance (indicated by the parameter μ), whereas no difference should be evoked between the active control conditions and the no-TMS baseline, as the control site is unlikely to participate in the picture naming process. However, should the presence of the pulse introduce marked changes in behaviour, the active control conditions could be used as a comparison category to all other TMS conditions, thus providing protection against possible placebo and non-neural effects that might be present in comparisons to the no-TMS baseline. Hence, a secondary analysis (contingent on the first analysis) was performed between the active control conditions vs. all target TMS conditions. To minimise pairwise comparisons and to facilitate the interpretability of the results, the active control conditions (C200 and C300) were averaged together to form a single control condition in the secondary analysis. Thus, the variable Condition had the following levels in the secondary analysis: Control, L200, L300, R200 and R300. The fixed effects for both primary and secondary comparisons were Language, Condition and Frequency, with all possible interactions included.

Results

Comparisons to the no-TMS baseline performance

A linear mixed model approach for rANOVA was used to test the influence of the TMS on the ex-Gaussian distributional measures. The primary fixed effects were Language (Finnish vs. Swedish), Condition (baseline, C200, C300, L200, L300, R200, and R300) and Frequency (high-frequency words vs. low-frequency words), as well as all interactions. Descriptives of the mean ex-Gaussian parameters on each level of the repeated effects is presented in Table 3.

Parameter μ

The analysis of the parameter μ revealed a significant main effect of Condition (F(6) = 26.587; p < .001) (Fig. 3A and B, the first row). Further pairwise comparisons showed that the parameter μ was highly similar between the baseline, the two active control TMS conditions and the R200 condition (p's > 0.05), indicating that TMS over the control site and over the right pIFG 200 ms post stimulus onset did not cause any significant delays to the naming latencies. However, compared to the baseline, the parameter μ was significantly increased for TMS conditions L200, L300 and R300 (p < .001). This indicates that TMS caused significant delays to the naming latencies when applied over the left pIFG 200 and 300 ms post stimulus onset and over the right pIFG 300 ms post stimulus onset.

Parameter σ

A statistically significant main effect of Condition was also observed for the parameter σ (F(6) = 9.21; p < .001) (Fig. 3A and B, the second row). Pairwise comparisons revealed a clear-cut effect between the baseline and all TMS conditions (p < .001), indicating a

Table 3
Descriptives (M, SD) of the three ex-Gaussian parameters on each level of the repeated effects.

	High		Low	
	FIN	SWE	FIN	SWE
μ				
BL	602.1 (79.4)	607.6 (67.6)	589.8 (52.7)	597.5 (90)
Left				
200 ms	636.7 (113.4)	654.6 (117.7)	632.2 (93.7)	640 (109.2)
300 ms	670.6 (116.3)	655.3 (106.1)	677.7 (127.6)	667.1 (117.1)
Right				
200 ms	629.7 (100.1)	615.8 (90)	636.9 (82.8)	622.7 (95.4)
300 ms	680.8 (128.9)	661.4 (92.9)	674.3 (116.6)	658.7 (100.3)
Control				
200 ms	591.5 (70.7)	602.8 (80.5)	587.8 (68)	594.8 (84)
300 ms	607 (77.6)	614.6 (95.2)	613.1 (77.1)	608 (84.6)
σ				
BL	73.3 (40.3)	77.7 (69)	52.7 (42.7)	82.1 (54.2)
Left				
200 ms	42.7 (35.2)	47.6 (48.4)	25.3 (27.5)	34.9 (26.4)
300 ms	39.8 (17.6)	44.7 (26.5)	35.1 (19.8)	43.4 (28.1)
Right				
200 ms	31.9 (22.4)	32.5 (15.2)	26.6 (21.1)	21.7 (14.4)
300 ms	39.4 (21)	39 (19.7)	36.3 (20.8)	45.1 (25)
Control				
200 ms	33.4 (15.5)	37.9 (21.7)	22.1 (21.8)	41.4 (26.1)
300 ms	33.1 (25)	33.7 (21)	32.6 (20.7)	41.1 (30.3)
τ				
BL	51.4 (43.5)	56.3 (48.7)	70.6 (43.2)	66.8 (46.6)
Left				
200 ms	113.6 (58)	88.7 (80)	142.3 (50.6)	106.1 (68)
300 ms	85.5 (59.8)	90.4 (59)	93.5 (48.3)	87 (62.1)
Right				
200 ms	104.4 (36.4)	139.2 (82.2)	114.1 (66.2)	118.7 (67.2)
300 ms	90.2 (59.5)	116.4 (63.3)	107.2 (49.5)	115.4 (56.2)
Control				
200 ms	103.6 (51.8)	108.1 (76.4)	117.3 (42.3)	108.9 (52.1)
300 ms	109.1 (49.7)	95.7 (73.3)	111.9 (54)	92.2 (54.4)

higher variability around the mean in the baseline condition vs. TMS conditions. The TMS conditions did not differ from each other (p's > 0.05).

Collapsing across Conditions, σ also differed significantly as a function of Language (F(1) = 8.39; p = .004) (Fig. 4 A) and Frequency (F(1) = 7.47; p = .007) (Fig. 4 B). There was more variability around the mean for Swedish vs. Finnish (M = 45.24, SD = 35.89 and M = 37.45, SD = 28.40 for Swedish and Finnish respectively) and for high-frequency words vs. low-frequency words (M = 45.02, SD = 32.00 and M = 37.67, SD = 32.77 for high-frequency and low-frequency words, respectively).

Parameter τ

There was a significant main effect of Condition (F(6) = 12.09; p < .001) (Fig. 3A and B, the third row) for the parameter τ. Pairwise comparisons revealed a clear-cut effect between the baseline and all TMS conditions (p < .001), indicating a higher occurrence of occasional slow naming latencies for all TMS conditions vs. the baseline. Furthermore, there was a significant interaction between Condition and Language (F(6) = 2.51; p = .027). Pairwise comparisons revealed that TMS to the left pIFG 200 ms post stimulus onset (condition L200) elicited significantly more occasional slow responses in Finnish than in Swedish (M = 127.94, SD = 55.41 and M = 97.42, SD = 73.48 for Finnish and Swedish respectively) (Fig. 3 B, the fourth row, grey background).
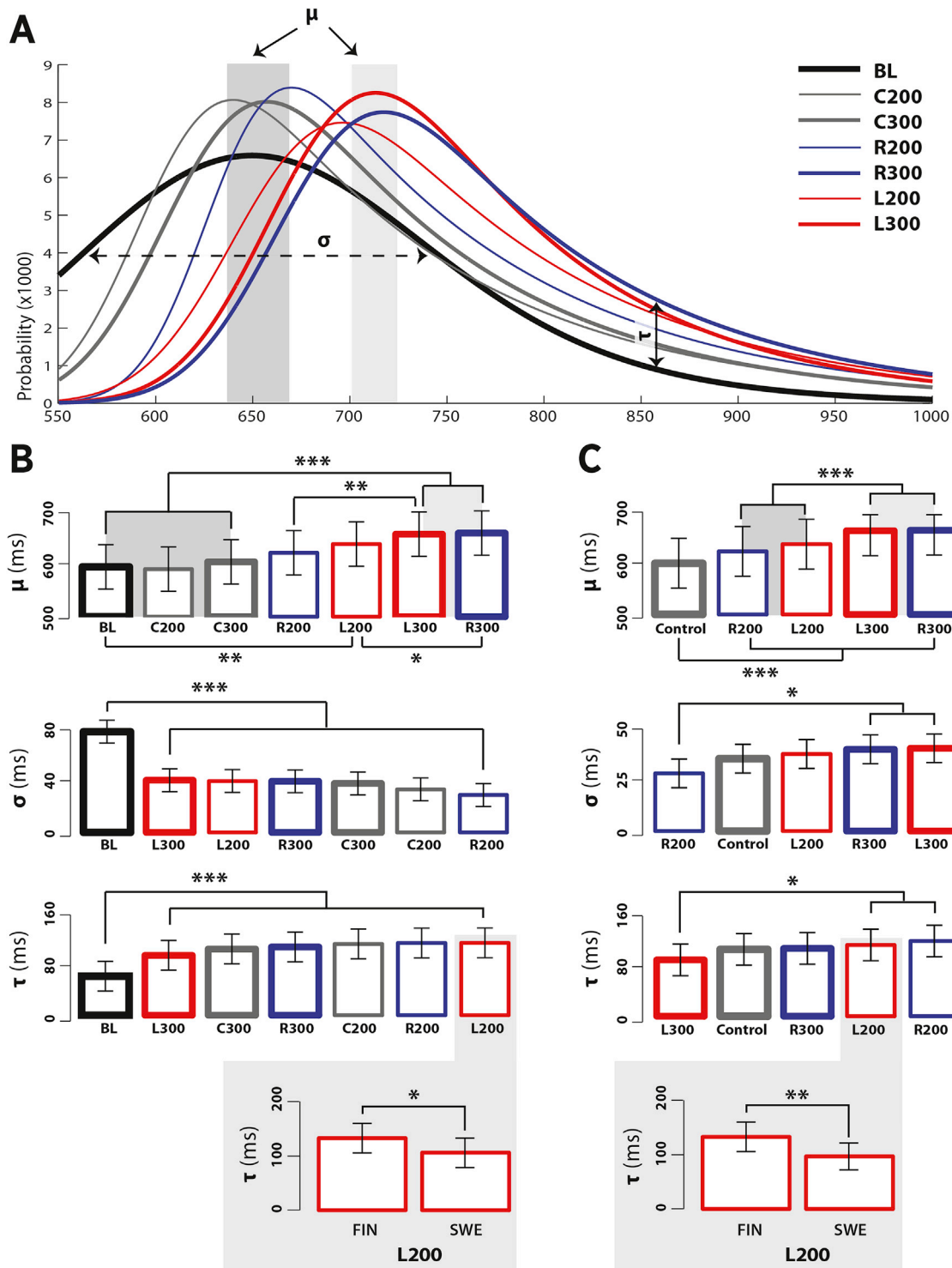
Fig. 3. **A)** Ex-Gaussian distributions of naming latencies across conditions and estimates of the ex-Gaussian parameters μ, σ, and τ (in ms) as a function of Condition, compared to **B)** the no-TMS baseline condition and to **C)** the averaged active control condition (error bars represent 95% confidence interval). On the grey background (the bottom row), is the interaction between Condition and Language on the parameter τ for condition L200, collapsing across Frequencies. Although all TMS conditions were associated with a higher occurrence of occasional slow naming latencies as compared to the baseline, TMS to the left pIFG 200 ms post stimulus onset elicited significantly more slow responses in Finnish than in Swedish. In the distribution plot, the grey bars highlight the distribution means (μ), the dashed horizontal line illustrates the distribution standard deviation (σ) and the solid vertical line illustrates the exponential component (τ). * = p < .05, ** = p < .01, *** = p < .001.

Comparisons to the active control condition

As the primary comparison revealed that the presence of the TMS pulse itself influenced participants' performance considerably

(revealed by the significant difference between the baseline vs. all TMS conditions, in particular with regard to parameters σ and τ) and since the active control conditions did not differ from each other in any of the comparisons, the secondary analysis was performed to more

A) LANGUAGE
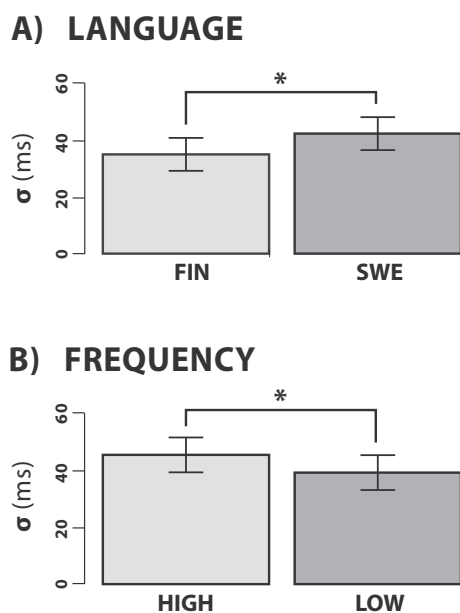
B) FREQUENCY

Fig. 4. The main effects of Language **A)** and Frequency **B)** on the parameter σ, collapsing across all conditions. The differences indicate a higher variability around the mean for Swedish vs. Finnish and for high-frequency words vs. low-frequency words. * = p < .05.

closely look at how TMS to different locations might have affected naming latency distributions relative to the averaged active control condition. Here, the primary fixed effects were Language (Finnish vs. Swedish), Condition (Control, L200, L300, R200 and R300) and Frequency (high frequency words vs. low frequency words), plus all interactions.

Parameter μ

There was again a significant main effect of Condition (F(4) = 26.34; p < .001) (Fig. 3 C, the first row). Compared to the averaged active control condition, the parameter μ was significantly increased for all target TMS conditions (p < .01 for all comparisons). Furthermore, the analysis revealed that there was a significant difference between conditions L300 and R300 vs. the L200 and R200 conditions (p < .001 between L300 and R300 vs. R200; p = .036 and p = .012 between L300 and R300 vs. L200, respectively), indicating that the TMS-induced naming latency delay was more pronounced with the later pulse timing.

Parameter σ

The main effect of Condition observed for the parameter σ with the primary analysis remained significant also with the secondary analysis (F(4) = 4.32; p < .01). However, the further pairwise comparisons revealed that, in fact, none of the experimental TMS conditions significantly differed from the active control condition (Fig. 3 C, the second row), suggesting that the variability around the mean was relatively stable across all TMS conditions (p's > 0.05 in all comparisons to the active control condition).

Similar to the primary analysis, significant main effects of Language (F(1) = 3.92; p < .05) and Frequency (F(1) = 5.89; p < .05) were observed. The pairwise comparisons confirmed that these effects were highly similar to those observed with the primary analysis, i.e. more variability around the mean for Swedish vs. Finnish and for high frequency words vs. low frequency words (see section 3.2.1).

Parameter τ

Also for the parameter τ, the main effect of Condition remained significant with the secondary analysis (F(4) = 5.04; p < .01). However, the

pairwise comparisons indicated that the experimental TMS conditions did not differ significantly from the active control condition (Fig. 3 C, the third row), suggesting that extremely delayed naming latencies occurred similarly across all TMS conditions (p's > 0.05 in all comparisons to the active control condition).

In line with the primary analysis, the interaction between Condition and Language remained significant and was even more pronounced in the secondary analysis (F(4) = 3.61; p = .008). This effect indicated again that TMS to the left pIFG 200 ms post stimulus onset (condition L200) elicited significantly more occasional slow responses in Finnish than in Swedish (Fig. 3 C, the fourth row, grey background).

Complementary analysis of the unperturbed naming latencies

Overall, bilinguals are often slower to name pictures compared to monolinguals and this delay is normally even more pronounced for L2 naming vs. L1 naming (for overview, see Hanulová et al., 2011). Contrary to these typical findings, our data indicated that participants were equally fast to name the pictures with both their languages (the parameter μ did not differ between the languages). Moreover, the unperturbed baseline naming latencies (estimates of the parameter μ) were highly similar to the average naming speed previously reported for monolinguals (Table 3: approximately 600 ms in the current study; 560–600 ms for monolinguals, estimated by Indefrey and Levelt, 2004).[3]

These results indicated that highly balanced, early simultaneous bilinguals might function as monolinguals when it comes to the picture naming speed. To confirm this finding, we compared the unperturbed bilingual naming latencies (collapsed across Languages) against a monolingual reference point, obtained from a small control group (N = 5, 1 male, mean age 24.8 years, SD = 2.59 years) of participants with only Finnish as their native language. The experimental procedure, including the anatomical and diffusion weighted MRI acquisitions as well as the TMS stimulation, was identical to the actual bilingual experiment. Regarding the data analysis, the ex-Gaussian distribution was fitted only to the naming latencies from the unperturbed baseline conditions and the obtained parameter μ was compared between the groups with an independent samples t-test. The parameter μ did not differ significantly between the monolingual and bilingual groups (t(19.47) = 0.758, p > .05), indicating that bilinguals were as fast to name the pictures as monolinguals.

Discussion

We investigated whether the neural basis sustaining speech production over the posterior IFG differs between the two native languages of a bilingual speaker during overt speech production. To tease apart the possible language-specific neural networks, online event-related anatomical and diffusion weighted MRI navigated TMS was delivered to the left and right pIFG separately, while balanced, early simultaneous bilinguals performed a picture naming task with their two native languages. The naming latencies were assessed by means of the ex-Gaussian approach that takes the distributional skewness of the test measures into account, and the resulting distributional parameters were compared between languages and across stimulation conditions with repeated measures mixed model analysis. Because the presence of the TMS pulse itself influenced participants' performance considerably relative to the no-TMS baseline condition, we focus on discussing only the findings that were significant in comparison to the active control

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[3] Note, that due to the routine practise of excluding outliers before averaging the individual RTs, the estimates of the parameter μ are directly comparable to the classic mean naming latencies reported e.g., by Indefrey and Levelt (2004). Here, instead of excluding delayed naming latencies as outliers, we used the parameter τ to represent them.

condition.[4]

Asymmetric TMS-induced changes between languages

Our main finding was that TMS affected naming performance in Finnish and Swedish differently when pulses were delivered to the left pIFG at 200 ms poststimulus. The difference was revealed by the parameter τ, indicating that stimulation elicited significantly more occasional slow responses in Finnish than in Swedish. In the absence of other significant TMS-induced between-languages effects, it is not explicitly clear whether this asymmetry is *qualitative*, indicating distinct language-specific neural populations, or *quantitative* in nature, possibly reflecting a language-specific difference in the activity state of a single shared language processing network. However, behavioural (Calabria et al., 2011; Costa and Santesteban, 2006, 2004) and electrophysiological (Duñabeitia et al., 2010) evidence from bilingual language switching studies has indirectly indicated comparable levels of activation between L1 and L2 for early simultaneous bilinguals, based on symmetrical switching costs between languages. Hence, it seems unlikely that quantitative differences in the activity state between the languages would have given rise to the observed effect. Moreover, based on previous findings suggesting that word frequency modulates activation levels within the language production network (Carreiras et al., 2006; Strijkers et al., 2010), we hypothesised that any between-language TMS effects stemming from differences in the relative activity state should be accompanied with similar TMS-evoked changes between high- and low-frequency words. Since no such frequency-related TMS-induced changes were observed, we propose that the current finding is likely to reflect the existence of language-specific neural networks. Thus, our finding not only adds to the accumulating evidence supporting functional separation of languages within the bilingual brain (Bloch et al., 2009; Fernández-Coello et al., 2016; Kim et al., 1997; Lucas et al., 2004; Ojemann and Whitaker, 1978; Perani et al., 2003; Roux et al., 2004; Roux and Trémoulet, 2002; Tussis et al., 2017; Walker et al., 2004; Xu et al., 2017), but also causally demonstrates, for the first time, that within a common language processing area, there are distinct language-specific neural populations for the different languages.

The fact that the effect was time-specific, that is, evoked only by stimulation delivered at 200 ms poststimulus (but not at 300 ms), suggests that functional activations over Broca's area at 200 and 300 ms post picture presentation might account for different aspects of the speech production process. According to Indefrey and Levelt's (2004) model, Broca's area receives activations from the posterior part of the left superior temporal gyrus, from where the individual phonemes that constitute the lexical item being produced are retrieved. In Broca's area, the retrieved segments are clustered together to form syllables (syllabification), which are then further processed into motor–action sequences

for the motor cortex to implement (phonetic encoding, articulatory preparation). Against this background, pulses delivered at around 200 ms poststimulus could disrupt mainly the syllabification process, whereas pulses delivered at 300 ms poststimulus could slow down the phonetic encoding process.[5] In line with this time-course proposal, previous TMS studies targeting the functional activations over the pIFG have shown that Broca's area is functionally relevant for overt word production at 300 ms poststimulus and no longer at 400 ms (Schuhmann et al., 2012, 2009; Wheat et al., 2013), suggesting that syllabification and phonetic encoding are already finished at around 400 ms poststimulus. Building on this, we propose that, at least for early simultaneous bilinguals, syllabification is a language-specific process sustained by distinct neural networks. On theoretical grounds, language-specific syllabification is justifiable, for phonotactic constraints governing the sequential arrangement of phonetic segments into morphemes, syllables, and words are indeed language-specific (Jurafsky and Martin, 2009). That is, even when languages share the same individual phonemes, a certain combination of those phonemes can be phonotactically legal in one language, while violating the rules for another language. For instance, phonemes /ö/ and /a/ are present in both Finnish and Swedish, however, only in Swedish can these phonemes appear together within a monomorphemic word (as in the infinitive form of the verb 'to drive', *köra*). Thus, we propose that the language-specific neural networks in Broca's area could support the implementation of language-specific phonotactics. Phonetic encoding/articulatory preparation, on the other hand, could be a more universal process, which takes the syllabified segments as input and produces motor action plans as output. Nevertheless, future research is needed to confirm these tentative suggestions.

Overall picture naming performance

One of the most frequently observed phenomenon concerning bilingual naming is the L2 naming delay, i.e., the finding that naming latencies are often significantly longer and more varied for the weaker L2 vs. L1 (Hanulová et al., 2011). Another regularly reported finding is that bilinguals are typically slower than monolinguals in producing names for objects, even when using their faster L1 (Gollan et al., 2008; Ivanova and Costa, 2008). In contrast, we observed equal unperturbed naming latencies for both languages (indicated by the parameter μ), with the obtained average naming latency matching the reported monolingual average (Table 3: approximately 600 ms in the current study, 560–600 ms for monolinguals, estimated by Indefrey and Levelt, 2004). These results suggest that the time-course for the overt speed production is highly similar between monolinguals and early simultaneous bilinguals. To confirm this, we asked a small control group of participants (N = 5) with only Finnish as native language to name the same pictures in a similar experimental setting and analysed their baseline naming latencies (see subsection 3.3 for more information). This comparison revealed no between-groups differences, substantiating that bilinguals named the pictures with a speed comparable to monolinguals. Although this finding was not anticipated, it is not completely implausible either: contrary to the bilingual samples used in most bilingual naming studies (for overview, see Hanulová et al., 2011), our participants were highly balanced across their languages. Even more importantly, they had a long history of balanced language exposure and usage, as over three quarters of them reported hearing and speaking both languages already in their childhood homes (Table 2, Languages in childhood). Thus, our data suggest that highly balanced early simultaneous bilinguals function as monolinguals when it comes to the picture naming speed. This finding provides indirect support to our interpretation concerning the language-specific neural networks, as native-like performance in both

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[4] TMS over the control site did not affect the parameter μ compared to the no-TMS baseline, confirming that the near vertex stimulation did not interfere with any task-related activity (Jung et al., 2016). However, subtler differences between the baseline and all TMS conditions we observed: the presence of the pulse resulted in decreased variability around the mean and evoked a higher occurrence of occasional slow naming latencies. As these changes were highly similar across all TMS conditions, they are likely to reflect the non-neural effects of the TMS, such as those evoked by the sound or skin sensation produced by discharging the TMS pulse (Jung et al., 2016). Alternatively, participants' beliefs and expectations related to receiving TMS might have caused their overall state of arousal to be heightened for TMS conditions vs. the no-TMS baseline, thus rendering the observed differences as placebo effects (Duecker and Sack, 2015). Note that stimulation over the fronto-temporal targets can cause stronger sensory effects than stimulation over the vertex. Thus, in theory, TMS can cause changes in naming performance solely due to discomfort related to fronto-temporal stimulation. Crucially, since the parameters σ and τ did not differ between the active control conditions vs. the fronto-temporal TMS targets, it is highly unlikely that any factors related to stimulation-induced discomfort could have significantly affected the naming performance. This is further supported by the fact that the primary analysis revealed no difference in the parameter μ between the baseline, the two active control conditions and the R200 condition.

[5] Note that we used quadruple pulses and thus pulses delivered at 200 ms disrupted processes taking place between 200 and 275 ms poststimulus and likewise, pulses delivered at 300 ms covered the time-window of 300–375 ms poststimulus.

languages can be thought to require native-like networks for both languages.

Despite the overall comparability of naming performance across languages and the apparent lack of the L2 naming delay, the responses were significantly more varied for Swedish compared to Finnish. In interpreting this finding, it is important to bear in mind that the parameter σ represents the SD of the mean from the classic central tendency analysis approach. As it is not customary to statistically compare changes in SDs *per se* within and across experimental conditions, it remains questionable whether this effect truly reflects some meaningful difference in the way the two languages are represented and processed or not. For this reason, some studies utilising the ex-Gaussian analysis have excluded the parameter σ from their statistical models, reporting only effects for the parameters μ and τ (e.g., Abutalebi et al., 2015; Zhou and Krott, 2016). Nevertheless, this finding could reflect a reminiscent of the L2 naming delay, as L2 naming latencies tend to be more varied than L1 responses (Hanulová et al., 2011). Consequently, the finding implies that Swedish might have been the (weaker) L2 for our participants, despite the fact that they self-evaluated their L1 and L2 language skills to be excellent. On trial-to-trial basis, naming latency variability has been shown to decrease as a function of repetition (Wingfield et al., 2006), suggesting that practice hones the performance towards a more stable level. Provided that the same applies also on a larger scale, the difference in the variability between the languages could be explained in terms of the participants' non-significant tendency to use Finnish somewhat more than Swedish (Table 2, Language usage). In other words, although the bilinguals were balanced enough not to exhibit the L2 naming delay, their language usage tended to favour the Finnish language and the parameter σ might have picked up this minor difference. This difference might have been further amplified by the fact that only Finnish was used throughout the experimental situation.

In the same vein, the parameter σ was also significantly different between the high- and low-frequency items. Contrary to the suggestion that σ decreases as a function of practise, the responses were more varied for high-frequency than for low-frequency words. As such, this finding contradicts most of the past frequency-related effects linking the production of high-frequency words to smaller functional activation levels (Carreiras et al., 2006) and faster reaction times (O'Malley and Besner, 2008), compared to those elicited by low-frequency words. Due to the obscurities related to interpreting the parameter σ (see above), we refrain from speculation on this difference further. Nevertheless, since neither of these σ effects reacted to the TMS stimulation, we conclude that, should they be related to some real processing differences between Finnish and Swedish and high- and low-frequency words, those differences do not rise from the subprocesses sustained by either the left or the right pIFG. Whether they originate from the processing stages preceding or following activation in these bilateral fronto-temporal locations, cannot be resolved with the current experiment.

Finally, although speech and language functions in right-handed monolingual populations are often highly left-lateralised (e.g., Cabeza and Nyberg, 2000), bilingualism has been shown to contribute towards a more bilaterally balanced structural (Hämäläinen et al., 2017) and functional (Hull and Vaid, 2007) language processing configuration. As the TMS-induced pattern of delays was symmetrical between the hemispheres (indicated by the parameter μ, the secondary analysis), our results corroborate these bilingualism-related findings in suggesting that bilingual speech production utilises both hemispheres. The results also indicate that the language processing networks over the left and right pIFG participate in speech production differently, for no language-specific effect (indicated by the parameter τ) was evoked by stimulating the right Broca's area homologue. Future studies are needed, however, to define whether the right pIFG might still participate in syllabification and/or phonetic encoding or perhaps supports some other aspects of speech production.

To conclude, our study revealed novel insights into the bilingual language organisation by demonstrating that even within common

language processing areas, distinct language-specific neural populations code for the different languages separately. Moreover, the time-window of the language-specific effect suggests that functional activations over Broca's area commencing at around 200 and 300 ms post picture presentation are likely to reflect different aspects of the speech production process, namely, syllabification and phonetic encoding. From a linguistic perspective, our finding associating language-specific processing with the syllabification stage is in concordance with the notion that the phonotactic rules governing the syllabification are highly language-specific; future studies are needed, however, to confirm these suggestions.

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