

Université de Montréal

**Influences de l'environnement linguistique prénatal sur  
l'émergence des réseaux langagiers à la naissance**

par

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Université de Montréal  
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*Cet essai doctoral intitulé*

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## Résumé

Au cours du développement, les réseaux cérébraux s'organisent pour traiter plus efficacement et mieux percevoir les stimuli les plus pertinents dans l'environnement. Déjà lors des premières heures suivant la naissance, les nouveau-nés montrent un traitement cérébral spécifique pour leur langue maternelle comparativement à des langues étrangères, ce qui se manifeste par une implication plus importante des réseaux fonctionnels de l'hémisphère gauche. Notre compréhension des origines de cette organisation fonctionnelle demeure toutefois limitée, notamment en lien avec l'expérience linguistique durant la période prénatale. Pour ce faire, nous avons étudié l'impact d'une exposition prénatale contrôlée à une langue étrangère sur le traitement cérébral et la spécialisation hémisphérique du langage à la naissance. Nous avons utilisé la spectroscopie près du spectre de l'infrarouge pour estimer la réponse cérébrale de 53 nouveau-nés à leur langue maternelle (français) ainsi qu'à deux langues étrangères (allemand et hébreu). Deux groupes avaient préalablement été familiarisés à l'une de ces langues étrangères durant leur dernier mois de gestation, alors qu'un groupe contrôle n'avait eu aucune exposition prénatale à ces stimuli. Nos résultats ont révélé une spécialisation hémisphérique en région temporo-pariétale gauche qui sous-tend le traitement de la langue maternelle à la naissance, et ce, indépendamment de l'expérience prénatale. Par ailleurs, les patrons de réponse cérébrale aux langues étrangères se distinguaient en fonction de la manipulation expérimentale de l'expérience linguistique prénatale. En effet, les nouveau-nés familiarisés à l'allemand *in utero* manifestaient notamment une activation plus grande et également latéralisée dans l'hémisphère gauche en réponse à l'allemand, ce qui n'était pas observé ni dans le groupe familiarisé à l'hébreu ni dans le groupe contrôle. Ceci suggère que l'organisation cérébrale à la naissance montrerait des traces d'apprentissage prénatal. Toutefois, la divergence des réponses en fonction de la langue exposée *in utero* sous-entend que cet apprentissage prénatal serait modulé par les propriétés phonologiques des langues. En somme, cet essai met en lumière l'implication tant de la familiarité, découlant de l'environnement linguistique *in utero*, que de caractéristiques phonologiques des langues dans le développement des réseaux langagiers durant la période périnatale.

**Mots-clés :** spectroscopie près du spectre de l'infrarouge; neurodéveloppement; nouveau-né; langue maternelle; familiarité; phonologie; apprentissage prénatal; activation cérébrale; spécialisation hémisphérique.

## Abstract

Throughout development, our brain networks adapt to environmentally relevant stimuli to enable a more efficient processing and to refine our perceptual abilities. From the first hours after birth, the newborn brain already displays a specialized processing of his/her native language in comparison to unfamiliar languages, revealed by a larger involvement of left hemispheric functional networks. However, our understanding of the origin of this functional brain organization remains limited, especially in regard to the influence of the linguistic experience during the prenatal stage. The current doctoral essay aims to better understand how the prenatal linguistic environment modulates the development of precursor language networks at birth. To do so, we investigated the impact of a controlled prenatal exposure to an unfamiliar language on the newborn brain processing and hemispheric specialization. We used functional near-infrared spectroscopy to estimate the brain responses of 53 newborns to their native language (French) and two unfamiliar languages (German and Hebrew). During their last month of gestation, two groups were repeatedly exposed to either one of the unfamiliar languages, while a control group received no prenatal exposure to those stimuli. Our results revealed that all newborns displayed a left hemispheric advantage in the temporo-parietal region for their native language, regardless of their prenatal exposure. Moreover, the experimental manipulation of newborns' prenatal experience triggered a differentiated response pattern when processing non-native languages. Indeed, German-exposed newborns exhibited a left asymmetry and an increased activation in response to the prenatally familiarized German, which was not observed in either the Hebrew-exposed or control newborns. This suggests that the cerebral organization at birth displays evidence of prenatal experience-dependent learning. However, the different cerebral patterns in regard of which language was exposed *in utero* indicate that phonological properties of the languages may modulate prenatal learning. In sum, this essay highlights that both familiarity, originating from the prenatal linguistic environment, and phonology shape brain language networks during early perinatal development.

**Keywords:** near-infrared spectroscopy; neurodevelopment; newborn; native language; familiarity; phonology; prenatal learning; brain activation; hemispheric specialization; speech processing.

## Structure de l'essai doctoral

Le présent essai doctoral prend la forme d'un article scientifique empirique portant sur les influences que l'environnement linguistique prénatal peut avoir sur l'émergence des réseaux langagiers et de la spécialisation hémisphérique dans le traitement du langage à la naissance. Cet article a été soumis au journal *Developmental Science* et est rédigé en anglais. De plus, un appendice a été ajouté à la suite du présent article pour ne pas alourdir ce dernier. L'appendice présente un portrait général des connaissances actuelles sur l'organisation cérébrale selon la spécialisation et l'intégration hémisphérique. La spécialisation hémisphérique des fonctions langagières est mise à l'avant-plan selon une vision historique, développementale, structurelle et fonctionnelle, puis est également discutée en relation avec d'autres fonctions cérébrales. Le contenu de cet appendice a paru sous la forme d'un chapitre en ligne au sein de l'*Encyclopædia Universalis* en 2018 et est rédigé en français. Ensemble, l'article scientifique et l'appendice permettent d'approfondir les connaissances actuelles sur l'organisation cérébrale des réseaux fonctionnels langagiers dans une optique développementale.

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## Liste des sigles et abréviations

$\eta_p^2$	Partial eta squared	RPA	Right pre-auriculars
ANOVA	Analysis of variance	SD	Standard deviation
cm	Centimeters	sec	Seconds
dB	Decibels	SI	Supplementary information
DPF	Differential pathlength factor	SPL	Sound pressure level
e.g.	<i>Exempli gratia</i> (for example)	$\alpha$	Alpha level
et al.	<i>Et alii</i> (et collègues / and colleagues)		
f0	Fundamental frequency (pitch)		
FDR	False discovery rate		
fNIRS	Functional near-infrared spectroscopy		
HbO	Oxyhemoglobin concentration changes		
HbR	Deoxyhemoglobin concentration changes		
HRF	Hemodynamic response function		
Hz	Hertz		
i.e.	<i>Id est</i> (namely)		
LH	Left hemisphere		
LPA	Left pre-auriculars		
min	Minutes		
MRI	Magnetic resonance imaging		
N	Number		
n.s.	Not significant		
nm	Nanometers		
OD	Optical density		
$p$	P-value		
$ps$	P-values		
PCA	Principal component analysis		
$r$	Pearson correlation coefficient		
RH	Right hemisphere		
ROI	Region of interest		

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## Article scientifique empirique

### **Prenatal exposure to an unfamiliar language: Both familiarity and phonology influence brain speech processing at birth**

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## **Abstract**

From birth, a basic cerebral network is dedicated to speech processing, which shares similarities with the adult brain. However, how prenatal experience modulates this network remains unknown. The current study investigated the impact of an experimental prenatal exposure to an unfamiliar language on the newborn's speech processing. In an fNIRS experiment, 53 newborns listened to their native language (French) and to two different unfamiliar languages (German and Hebrew). Prior to birth, during the last gestational month, two groups were repeatedly exposed to the stimuli both in their native language and in either one of the unfamiliar languages, while a control group had no prior exposure to these stimuli. Our results revealed that the experimental prenatal manipulation modulated the brain response in the temporo-parietal region. While all newborns displayed a left hemispheric advantage for their native language, German-exposed newborns also exhibited a left dominance for the non-native languages, and an increased activation in response to the prenatally familiarized German. These patterns were not observed in either the Hebrew-exposed or control newborns. These results reaffirm the early existence at birth of specialized processing for the native language. More importantly, it implies that even if short, exposure *in utero* to an unfamiliar language influences neonatal speech processing. However, the different brain patterns across groups suggest that phonological properties of the languages, such as speech rate and pitch, may modulate prenatal experience-dependent learning. It thus reveals that both familiarity, acquired through prenatal experience, and phonology likely shape brain language networks during early perinatal development.

## **Research highlights**

- We investigated how prenatal experience shapes brain speech processing at birth through experimental exposure to native French and either unfamiliar German or Hebrew *in utero*.
- By comparing newborns' fNIRS responses to native and unfamiliar languages, we observed a specialization for the native language, indexed by a temporo-parietal left hemispheric advantage.
- Experimental manipulation of the prenatal linguistic experience, through repeated exposure to an unfamiliar language, triggered a differentiated cerebral response at birth in the temporo-parietal region.
- An advantage for only one of the prenatally familiarized languages suggests that both the language's familiarity and its phonological features influence speech processing.

## 1. Introduction

In the field of developmental neuroscience, evidence cumulated over the last few decades has shed light on the neurobiological origins of human language abilities. Throughout its development, the brain adapts to linguistically-relevant sounds, in order to enable efficient information processing and refine linguistic perception (Byers-Heinlein & Fennell, 2014; Herve et al., 2013; Kuhl, 2010; Wang et al., 2014). Even at birth, the brain already has in place a basic network dedicated to speech and language processing that is highly similar to the adult language network. Specifically, the bilateral temporal and left inferior frontal areas have been found to be involved in the processing of speech and language stimuli in newborns (Gervain et al., 2008; May et al., 2011, 2017; Peña et al., 2003; Perani et al., 2011; Saito et al., 2007; Vannasing et al., 2016). An emerging left hemispheric dominance is noticeable in newborns as early as one day after birth, at least for the native language (Peña et al., 2003; Vannasing et al., 2016). It has been proposed that the lateralization of speech processing may be driven by a stronger involvement of the left hemisphere in the processing of fast modulated sounds, such as phonemes, while slower modulations that convey the prosody of speech may preferentially be processed in the right hemisphere (Telkemeyer et al., 2009; Zatorre & Gandour, 2007; although see Poeppel (2014) regarding this position).

While the newborn brain has a very limited amount of postnatal experience, insights gained on the prenatal period may help us better understand the early emergence of brain specialization for speech and language processing. Fetuses are exposed extensively to acoustic stimulation while *in utero*, as the auditory system is already functional by the end of the second trimester of gestation (Ghio et al., 2021; Partanen & Virtala, 2017). Even with the presence of internal background noise, originating predominantly from the placenta and the mother's cardiovascular system, external sounds are relatively well transmitted *in utero*, notably those with frequencies lower than 250-400 Hz (Busnel et al., 1992; Querleu et al., 1988). Maternal tissues and the amniotic fluid act as low-pass filters, which greatly reduces most segmental information in the speech signal (Busnel et al., 1992; Griffiths et al., 1994; Querleu et al., 1988), while prosody is preserved (Granier-Deferre et al., 2011a, 2011b). Prosodic information, such as intonation and rhythm, is considered of utmost importance in language acquisition. Newborns recognize the prosodic patterns they experienced prenatally (Abboub et al., 2016; Martinez-Alvarez et al., 2022), and already rely on prosodic contours to segment the continuous speech flow in their surrounding environment (Fló et al., 2019).

This sensitivity to prosodic cues might underlie the newborn's ability to distinguish between languages that have different rhythms (e.g. Spanish and English), but not those whose rhythms are similar (e.g. English and Dutch) (Nazzi et al., 1998a; Ramus et al., 2000).

An increasing body of literature suggests that speech perception and language processing are shaped by prenatal experiences. Prior to birth, near-term fetuses already show an orienting response to familiar stimuli, for instance a story that had been repeatedly recited by their mothers during pregnancy (Ghio et al., 2021; Krueger & Garvan, 2014). Newborns also demonstrate a general preference for familiar over unfamiliar linguistic stimuli (Byers-Heinlein et al., 2010; Kisilevsky et al., 2003, 2009; Moon et al., 1993). This early preference for familiar speech, voices, and sounds is not only observed at the behavioral level, but has also been observed in the brain by using neuroimaging techniques such as functional near-infrared spectroscopy (fNIRS) and electrophysiology (Beauchemin et al., 2011; May et al., 2011, 2017; Sato et al., 2012; Vannasing et al., 2016). The neonatal brain generally displays enhanced brain responses to the native language, compared to unfamiliar languages. In some studies, this enhanced response was located in the bilateral fronto-temporal areas (May et al., 2011, 2017), while in others, it was more left-lateralized (Sato et al., 2012; Vannasing et al., 2016). There is also evidence that the brain speech processing, particularly in the temporo-parietal areas, is sensitive to the prosodic patterns of the languages newborns were exposed to while *in utero* (Abboub et al., 2016), such as final lengthening, typical in French (i.e. iambic patterns), or initial pitch-based prominence, typical in Farsi or Korean (i.e. trochaic patterns).

While the current evidence demonstrates the ability of fetuses and newborns to recognize language stimuli with which they gained familiarity during the prenatal period, the underlying cerebral response patterns have not been consistently identified across studies. Moreover, it remains difficult to generalize such findings, as most studies only employed one unfamiliar language, and therefore had possible confounding effects from acoustic and rhythmical differences between the native and unfamiliar language (Arvaniti & Rodriguez, 2013). Furthermore, most studies based their conclusions on observational data, and had no control on the prenatal linguistic environment of newborns. These limitations restrict our understanding of the actual mechanisms that underlie experience-dependent plasticity occurring *in utero* in response to the prenatal acoustic and linguistic environment. To our knowledge, only one group has investigated how prenatal



exposure to musical and linguistic stimuli modulates the neural networks that underlie auditory discrimination and recognition in infants (Partanen et al., 2013a, 2013b). Using electrophysiology, these studies demonstrated that repeated exposure to a specific lullaby or a basic speech unit, /ta/, during the last trimester of gestation could modulate the neural activity underlying the discriminative processing of those stimuli, with some effects even persisting for up to four months after birth. These results suggest that fetal brain development is tuned to its auditory environment. It remains unclear to what extent *in utero* experience-dependent plasticity also applies to language networks.

In the current study, we aimed to expand our understanding of the role played by the prenatal linguistic environment in neonatal language processing. More specifically, by introducing an unfamiliar language into the linguistic experience of a group of fetuses, we investigated how the prenatal environment shapes language processing at birth, especially with regard to hemispheric dominance for speech and language in the temporal and inferior frontal regions.

To do so, we examined the newborns' brain responses to their native language, French, and two unfamiliar languages, German and Hebrew, using fNIRS in the first few days after birth. We manipulated familiarity, as a group of infants were repeatedly exposed to the same short children's story in both their native language and in one of the unfamiliar languages during their last month of gestation. An additional control group had no exposure to either story during gestation. German and Hebrew were chosen as the unfamiliar languages, because they are both stress-timed languages, and therefore one would expect that newborns would be able to discriminate them from French, which is syllable-timed (Nazzi et al., 2006; Segal et al., 2009, 2015). Furthermore, even though German and Hebrew are both rhythmically different from French, Hebrew shows more phonological similarities to French. The two languages have similar vowel repertoires (Ravid & Shlesinger, 2001) and typically use iambic patterns, such as word- or phrase-final stress (Bijeljac-Babic et al., 2012; Nazzi et al., 2006; Segal et al., 2015), while German mainly has word-initial lexical stress (trochaic patterns; Höhle et al., 2009). Because newborns have been shown to respond to familiar stimuli and be sensitive to the prosodic and phonological properties of the languages heard prenatally (Abboub et al., 2016; Langus et al., 2017; Martinez-Alvarez et al., 2022), we expected different brain responses in the fronto-temporal language areas to the three languages, as a function of familiarity and linguistic similarity.

## 2. Materials and methods

### 2.1. Participants

Seventy-six healthy pregnant women and their future newborns were recruited during their third trimester of pregnancy, while at one of their antenatal visits to the obstetrics and gynecology clinic associated with the Sainte-Justine University Hospital. They all had a normal, singleton pregnancy, without complications (e.g. no pre-eclampsia, gestational diabetes, congenital anomaly, fetal growth restriction) and no history of substance abuse, psychiatric or neurological disorder. All mothers and their respective partners spoke French as their native language, used daily in the household. Each newborn's eligibility was reassessed after birth by reviewing their medical records. They were excluded if born < 37 gestational weeks, weighed < 2,500 grams, had an APGAR score < 7 at 5 or 10 minutes, were suspected of having an auditory deficit, or if the condition of their health required a stay at the neonatal intensive care unit. The study was approved by the Research Ethics Committee of Sainte-Justine University Hospital, and informed written consent was obtained from all parents.

Based on whether they were recruited prior or after their 35<sup>th</sup> week of pregnancy, women were respectively assigned to one of the experimental prenatal groups (N=43) or to the control group (N=33). Women in the prenatal groups were then randomly assigned to one of the two following subgroups: German (N=22) or Hebrew (N=21) prenatal exposure. Out of all 76 recruited participants, 23 were excluded due to a variety of reasons: neonatal complications (N=9), cancellation of the visit at birth due to the Covid pandemic (N=5), insufficient fNIRS data due to fussiness or crying (N=4), withdrawal of participation after delivery (N=2), an insufficient amount of prenatal exposure (i.e. less than one session every other day; N=2), and a technical problem with the fNIRS system (N=1). Data from the remaining 53 newborns were analyzed, for a total of 20 control neonates and 33 newborns in the prenatal groups ( $N_{\text{German}}=17$ ,  $N_{\text{Hebrew}}=16$ ).

Demographic and clinical information were collected from medical records and through parental reports. No statistically significant differences were found across groups in regard to medical and sociodemographic variables (see Table 1 for a description of the sample).

**Table 1. Summary of participant characteristics**

Characteristics	Control group	Prenatal groups		<i>p</i> -value
		German	Hebrew	
Sex (N female)	9 (45%)	10 (59%)	9 (56%)	.666
Gestational age at birth (weeks)	40.1 ± 1.0	39.7 ± 0.8	39.6 ± 1.0	.174
Age at testing (hours)	30.9 ± 12.2	31.2 ± 16.4	28.3 ± 11.2	.792
Age at testing (gestational weeks)	40.3 ± 1.0	39.9 ± 0.8	39.7 ± 1.0	.154
APGAR at 5 min	8.9 ± 0.7	8.8 ± 0.7	8.9 ± 0.5	.976
APGAR at 10 min	9.1 ± 0.2	8.9 ± 0.5	9.1 ± 0.3	.224
Birth weight (grams)	3525 ± 574	3416 ± 385	3406 ± 421	.701
First child (N)	11 (52%)	9 (52%)	6 (38%)	.537
Mother's age (years)	32.0 ± 3.7	33.0 ± 4.8	33.1 ± 1.5	.565
Father's age (years)	34.2 ± 3.9	34.8 ± 3.7	34.7 ± 5.5	.936
Maternal level of education (N of university degree)	16 (80.0%)	14 (82.3%)	14 (87.5%)	.834
Paternal level of education (N of university degree)	15 (78.9%)	11 (68.7%)	13 (93.3%)	.551
Maternal socioeconomic status <sup>a</sup>	76.4 ± 16.3	77.4 ± 20.8	86.3 ± 14.4	.195
Paternal socioeconomic status <sup>a</sup>	74.7 ± 19.9	79.0 ± 15.6	79.5 ± 19.2	.682
Number of completed prenatal exposure sessions (days)	N/A	25.4 ± 7.6	24.7 ± 8.4	.800

*Note.* Mean and standard deviation are represented for continuous variables, while frequency and percentage are represented for categorical variables. Statistical difference was obtained by a one-way analysis of variance for continuous variables, and chi-square test of independence for categorical variables.

<sup>a</sup> A higher score indicates a higher socioeconomic status on the Canadian adaptation of the Nam-Powers-Boyd occupational scale (Boyd, 2008).

## 2.2. Procedure

### 2.2.1. Prenatal exposure

Starting in the 35<sup>th</sup> week of gestation, fetuses from the prenatal groups were exposed daily to two versions of the same children's story: one in their native language (i.e. French) and one in a non-native language (i.e. either German or Hebrew, according to their respective subgroup). This gestational period was chosen because an orientation response to complex speech stimuli has been previously documented for fetuses of this age, compared to younger fetuses (Kisilevsky et al., 2003, 2009; Krueger & Garvan, 2014). Once again, the control group was exposed to none of these stimuli during gestation.

All mothers included in the experimental prenatal groups were given the same audio kit, which contained a portable audio player and headphones (Sony MDRZX110). Mothers were instructed to complete one prenatal exposure session daily until delivery, with a minimum of once every two days. During each session, they placed the headphones on their abdomen, at the approximate position of their child's head. The daily prenatal exposure session lasted 20 minutes, during which each language version of the 5-minute story was presented twice in alternation. The first language in the recording was counterbalanced across participants. The volume had been calibrated beforehand in the laboratory to 90 dB, to account for sound attenuation across maternal tissues, thus yielding approximately 60 dB *in utero* and posing no risk to fetal auditory development (Arulkumaran et al., 1992; Granier-Deferre et al., 2011a, 2011b; Querleu et al., 1988). Mothers were instructed to complete the sessions in a calm environment, with no surrounding conversations or other verbal or auditory interference (e.g. no television with the sound on, no listening to music or speaking during the session). They completed a diary in order to keep track of the number of completed daily sessions and the surrounding conditions.

### 2.2.2. Stimuli

The French, German, and Hebrew versions of the children's story were all recorded by the same multilingual female speaker, fluent in all three languages. She was instructed to read the stories as though she were telling them to an infant, so as to maximize infant-directed speech. Each language version included a total of 18 blocks, each with a mean duration of  $15.1 \pm 0.1$  seconds [sec]. The mean intensity of all blocks was normalized, and a 3-sec fade-in and fade-out (starting and ending at 60 % of mean intensity) were applied using Audacity 2.2.1 (The Audacity Team) To create a continuous 5-minute story for each language version of the prenatal exposure material, all 18 blocks of each language were juxtaposed, with 0.8-sec pauses in between the blocks. The same stimuli were used for prenatal exposure and fNIRS testing around the time of birth.

For each stimulus block, mean pitch ( $f_0$ ), maximal  $f_0$  and standard deviation of  $f_0$  were extracted using Praat v.6.1.32 (University of Amsterdam) and the number of syllables was counted by a native speaker and further validated by a second independent listener (Arvaniti & Rodriguez, 2013; Boersma, 2014). To estimate pitch variability within each block, a normalized metric (i.e. standard deviation  $f_0$  relative to mean  $f_0$ ) was further computed (Zimmerer et al., 2014). Table 2 shows the summary of the main acoustic parameters across language conditions.

**Table 2. Acoustic properties of stimuli**

Metrics	Language conditions			Significant difference ( $p < .05$ )
	French (F)	German (G)	Hebrew (H)	
Mean f0 (Hz)	196.0 $\pm$ 7.3	203.5 $\pm$ 11.7	185.7 $\pm$ 7.0	G > F > H
Maximal f0 (Hz)	386.8 $\pm$ 61.7	385.5 $\pm$ 42.6	362.0 $\pm$ 50.8	n.s.
Standard deviation f0 (Hz)	42.1 $\pm$ 7.5	45.5 $\pm$ 5.9	38.2 $\pm$ 6.7	G > H
f0 variability (normalized)	0.21 $\pm$ 0.03	0.22 $\pm$ 0.02	0.21 $\pm$ 0.03	n.s.
Speech rate (syllables/sec)	4.0 $\pm$ 0.2	3.4 $\pm$ 0.2	4.6 $\pm$ 0.3	H > F > G

*Note.* Mean  $\pm$  standard deviation was computed based on the 18 stimulus blocks for each condition.

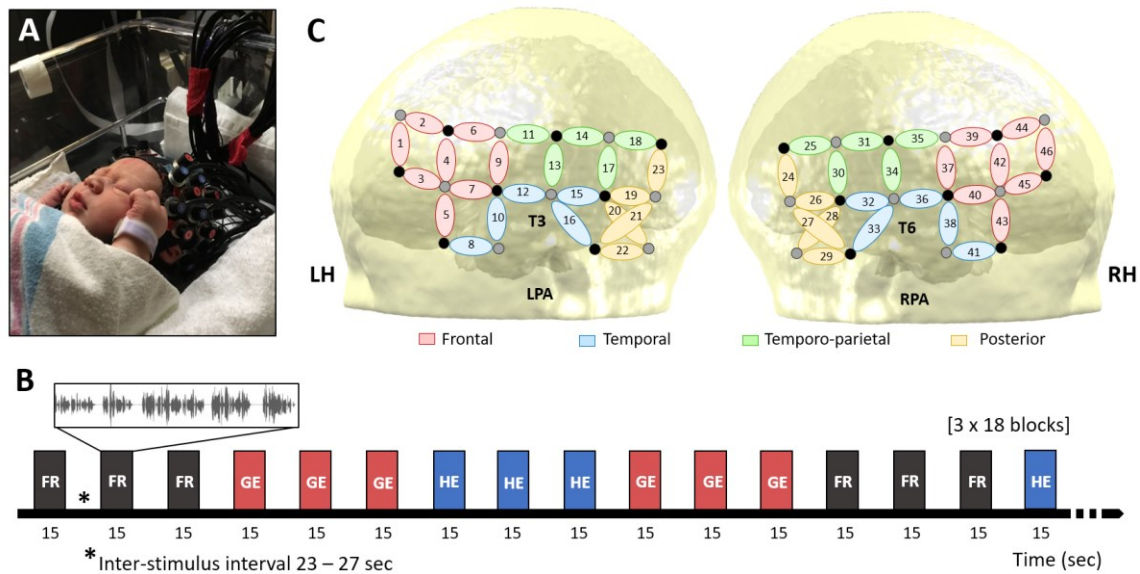
Statistical difference was obtained by a one-way analysis of variance. *N.S.* refers to non-significant.

### 2.2.3. Neonatal fNIRS recording

fNIRS has been widely used with newborns, as it is a non-invasive functional imaging technique that is relatively tolerant to movement (de Roeve et al., 2018). This technique is based on the light absorption properties of oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentrations within the near-infrared spectrum. It provides an estimate of cerebral activity that is based on neurovascular coupling through the measurement of relative hemodynamic concentration changes. fNIRS can be used to explore brain functioning and organization and has been successfully employed in the past to investigate the cerebral correlates of speech processing and early language abilities in newborns and infants (Gervain et al., 2011; Lloyd-Fox et al., 2010).

Newborns underwent an fNIRS recording in their first days of life, before being discharged from the postpartum unit at the Saint-Justine University Hospital. Age at recording ranged between 10 and 78 hours after birth. The recording session occurred in a soundproof room after the newborns had been fed and while they lay asleep on their backs, either in their hospital crib or on a cushion placed on their parent's lap (Figure 1A). All newborns listened to the story in each of the three languages, i.e. French, German, and Hebrew. The stimuli were played through two speakers positioned at about 70 cm from the newborn's head, where the intensity reached approximately 70 dB, as measured by a sound meter. The stories were presented using a block design paradigm, with 18 blocks per language condition. The 15-sec stimulation blocks were separated by silent interstimulus intervals that lasted between 23 and 27 sec (Figure 1B), yielding an approximate total duration of 36 minutes. The switch between language conditions occurred after the presentation of three consecutive blocks from one language. Languages were presented in a pseudo-random order,

with the starting language and the order of languages counterbalanced across newborns (each language condition followed every other language condition equally often).



**Figure 1.** Experimental procedure for the fNIRS recording at birth. (A) A newborn participant wearing the fNIRS cap in its crib. (B) Example of the experimental paradigm, with language conditions alternating after the presentation of three consecutive blocks (French in black, German in red, and Hebrew in blue). (C) Probe placement and their approximate spatial projection onto a newborn MRI brain template (Kazemi et al., 2007). Coupling of light sources (gray dots) and detectors (black dots) yielded a total of 46 channels (colored ovals). Colors represent the four ROI subdivisions of the LH and RH based on anatomical landmarks and 10-10 coordinates.

fNIRS data acquisition was performed using a continuous-wave NIRScout system (NIRx Medical Technologies) equipped with 16 detectors and 16 sources of 760 nm and 850 nm wavelengths, and a sampling rate of 7.8 Hz. The montage included 46 channels with a ~2 cm source-detector distance. Detectors and sources were held in place by a flexible cap (Easycap GmbH). The positioning of the cap was standardized across newborns using their head circumference, nasion-inion distance, and the left (LPA) and right (RPA) pre-auriculars as references. A pediatric nurse was present during the session to ensure each participant's well-being and to make sure the cap remained stable in case of fussiness. The probes were positioned to cover the temporal lobe and parts of the frontal and parietal lobes symmetrically for both left (LH) and right (RH) hemispheres (Figure 1C). Following the procedure described by Lloyd-Fox and

colleagues (Lloyd-Fox et al., 2014), spatial localization of each probe relative to fiducial points (nasion, inion, LPA, RPA) was digitalized on a newborn head model, using the Polaris stereotaxic system (Northern Digital Inc) and Brainsight Frameless 39 software (Rogue Research Inc). It was then co-registered onto a newborn structural MRI template (Kazemi et al., 2007) and visualized with the 3DMTG interface from the LIONirs toolbox (Tremblay et al., 2022). Anatomical registration was further validated in accordance with the international 10-10 system (Kabdebon et al., 2014). This procedure made it possible to estimate the cerebral regions underlying each channel and to derive four main regions of interest (ROI) comparable with other infant studies (Abboub et al., 2016; Benavides-Varela et al., 2017; Gervain et al., 2008; Mercure et al., 2020). The *frontal region* covered parts of the inferior, middle, and precentral gyri. The *temporal region* covered the area around the superior temporal sulcus, mostly the superior and middle temporal gyri, and the anterior temporal pole. The *temporo-parietal region* encompassed brain areas around the temporo-parietal junction, such as the posterior part of the superior temporal, the supramarginal and the angular gyri. The *posterior region* included the posterior part of the inferior temporal gyrus and parts of the occipito-temporal and parieto-occipital regions.

A balloon-type respiration belt and an oximeter were placed on the newborn's abdomen and big toe, respectively. They measured the respiratory rate, heartbeat, and blood pressure fluctuations, which are all known to represent systemic physiological confounds in fNIRS data (Yücel et al., 2021). These auxiliary data were acquired simultaneously to the fNIRS data at a sampling rate of 500 Hz using the ActiChamp system and Brain Vision Recorder v1.2 (Brain Products) and synchronized with fNIRS data by using task-associated triggers generated by the experimental software Presentation (Neurobehavioral Systems). The newborns' movements (e.g. sucking, startles) were filmed to validate movement artifact identification in offline analyses.

## **2.3. Data analyses**

### *2.3.1. Data processing*

fNIRS data processing was conducted using the LIONirs toolbox (Tremblay et al., 2022), which is embedded in the SPM12 toolbox (Penny et al., 2011) and runs using Matlab R2020a (MathWorks). Raw light intensity data were imported, and trials were extracted starting 5 sec before stimulus onset and ending 20 sec after stimulus offset, yielding a total trial length of 40 sec. A signal quality check was performed based on the cardiac pulsation (targeted between 1 and 3 Hz) cross-

correlation across wavelengths for each channel, in line with Pollonini and colleagues (2014). A high correlation coefficient ( $r > 0.75$ ) indicated sufficient signal quality for inclusion in further analysis.

Movement artifacts, represented by abrupt amplitude changes in the signal, were identified using an automatic detection algorithm with a moving average technique (Tremblay et al., 2022). The amplitudes that exceeded three standard deviations within each 1-sec time window were identified as representing artifacts. Furthermore, neighboring channels that were highly temporally correlated ( $r > 0.8$ ) were also identified as having been affected by the same artifact event. A thorough visual inspection was conducted afterwards to verify and adjust, when appropriate, the artifact detection process.

The use of trial rejection alone to deal with motion artifacts has been discouraged in the fNIRS literature, even for infant data, because it greatly reduces the quantity of valid trials and influences the recovery of the hemodynamic response function (HRF) in the data (Brigadoi et al., 2014; Di Lorenzo et al., 2019). On the other hand, motion correction algorithms can also reduce the HRF amplitude (Gemignani & Gervain, 2021), and should only be employed when the data is of sufficient quality (Yücel et al., 2021). We therefore employed a two-step artifact correction method because of our large number of trials and of our aim of comparing response amplitude across different language conditions. First, individual channel-by-trial pairs were rejected if movement occurred during the stimulation periods (i.e. 0 to 15 sec) and shortly before or after (i.e. 5 sec), or if more than 15% of the trial duration was comprised of movement artifacts (Paquette et al., 2015). The artifacts present in the remaining data were corrected using target principal component analysis (PCA) (Alexopoulos et al., 2021; Yücel et al., 2014). This decomposition technique was chosen because of its good performance when correcting infant motion artifacts, especially when a large number of channels are available (Di Lorenzo et al., 2019), as was the case in our study. Target PCA was implemented for each artifact event and all channels were included for data decomposition. We then applied an offset adjustment to counteract abrupt shifts that followed artifact-related events (Scholkmann et al., 2010).

Data were then converted into optical density (OD) changes and then transformed into relative oxy- and deoxyhemoglobin concentration changes (HbO and HbR, respectively) using the



modified Beer-Lambert law with an age-appropriate differential pathlength factor (DPF) (Scholkmann & Wolf, 2013) ( $DPF_{760nm} = 5.286$ ;  $DPF_{850nm} = 4.224$ ).

To account for physiological confounds, we first applied a fourth-order Butterworth bandpass filter with cut-off frequencies of 0.01-0.5 Hz, to remove low- and high-frequency noise (e.g. slow drifts and heartbeat). Temporary symmetrical padding at the start and end of trials was used to avoid signal deformation around their edges. To further minimize systemic physiology that falls within the frequency range of the HRF, variations that could be accounted for by the auxiliary respiratory and blood fluctuations were regressed out from the fNIRS data (Kirilina et al., 2013; Tachtsidis et al., 2010). More specifically, auxiliary signals were first normalized and sampled down to match the fNIRS data (von Lühmann et al., 2020). An automatic motion artifact detection was performed to find abrupt changes that exceeded an initial standard threshold (i.e. 0.5 SD), using a moving time window (Scholkmann et al., 2010). As the data quality varied according to the level of the newborn's fussiness, the threshold was readjusted for each individual, after initial artifact detection. Artifacts were corrected using spline interpolation (Scholkmann et al., 2010), and the cardiac and respiration signals were then filtered, using the same parameters as were used for the fNIRS data. The variance in the fNIRS data that could be explained by the time-corresponding auxiliary signals was then regressed out using a general linear model. Finally, a baseline was linearly fitted between the mean of the initial 5 sec (i.e. the baseline segment) and the last 5 sec of each trial, and subtracted from the fNIRS signal (Gemignani & Gervain, 2021).

For each participant, the average HbO and HbR responses were computed by averaging artifact-free trials for each language condition and channel, with the requirement to reject the channel if it had fewer than four valid trials per condition. On average, there were  $10.3 \pm 2.7$  valid trials per participant in the French condition,  $9.8 \pm 2.8$  in the German condition, and  $9.7 \pm 3.1$  in the Hebrew condition. A mixed analysis of variance (ANOVA) computed on the number of valid trials did not reveal any significant difference between language conditions, groups or the interaction between these variables ( $ps > .05$ ).

Because there is great variability across the infant HRF (Issard & Gervain, 2018), we identified the time window around maximal activation by visually inspecting the grand average across all newborns, language conditions, and channels. (Lloyd-Fox et al., 2019; Mercure et al., 2020). HbO concentration changes peaked around 10-12 sec, while the HbR peak occurred

approximately 2 sec later. These maximal timings were consistent with other newborn studies that have used speech stimuli of a similar type and duration (May et al., 2011, 2017; Vannasing et al., 2016). Mean HbO amplitude between 7 and 15 sec after stimulus onset (i.e. around maximal activation) was thus extracted for statistical analysis. The analysis time window for HbR was between 9 and 17 sec.

### 2.3.2. Statistical analysis and ROI selection

To determine which cerebral regions were recruited for processing the different language conditions, mean amplitude was first statistically compared against the silent baseline in each language condition and channel using two-tailed paired samples *t*-tests. To do this, we grouped together all newborns (Tak & Ye, 2014). Due to individual channel rejection criteria, *t*-tests were based on an average of  $51.1 \pm 1.3$  participants (ranging between 48 and 53). Analyses were carried out independently for HbO and HbR. We applied the false discovery rate (FDR) correction (Benjamini & Hochberg, 1995) to control for multiple comparisons.

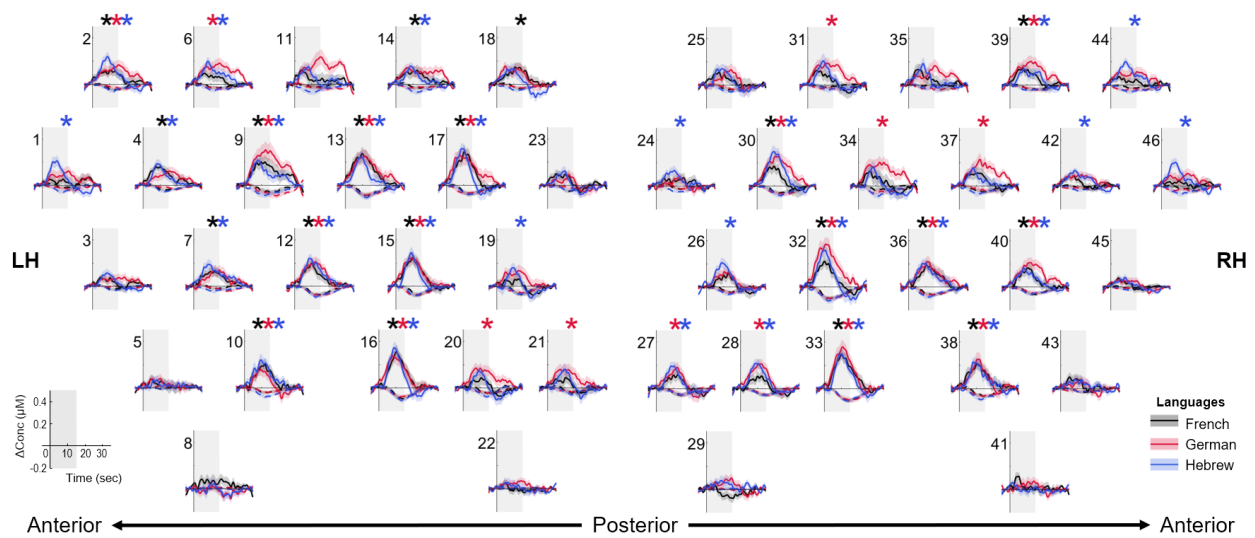
To statistically assess differences across groups and language conditions, only the channels that showed a significant increase in HbO in at least one of the conditions were used (see Results section 3.1 below, and Supplementary information (SI) for detailed information). To ensure symmetry between hemispheres, non-significant channels were included only when their homologous counterpart revealed a significant response (Benavides-Varela & Gervain, 2017). The same channels were selected for HbR, because HbO signal changes have been found to more reliably indicate neural responses in infants (Gervain et al., 2011; Lloyd-Fox et al., 2010). Channels located within the same ROI were further averaged together to obtain the mean concentration change for each ROI. Three participants were not included in this analysis, as they did not have at least two valid channels within each ROI for each hemisphere and language condition, thus yielding a total of 50 included participants ( $N_{\text{Control}}=18$ ,  $N_{\text{German}}=16$ ,  $N_{\text{Hebrew}}=16$ ). A mixed ANOVA including the between-subject factor *Group* (Control, German, Hebrew) and within-subject factors *Language* (French, German, Hebrew) and *Hemisphere* (LH, RH) was computed on the HbO and HbR concentration changes within each ROI. FDR was used to correct for multiple comparisons occurring from the four ROI analyses, and Greenhouse-Geisser sphericity corrections were applied when appropriate. Post-hoc pairwise comparisons were carried out with FDR correction. Effect

sizes were estimated using partial eta squared ( $\eta_p^2$ ). Significance level was set to  $\alpha = 0.05$ . All statistical analyses were carried out using Matlab R2020a.

### 3. Results

#### 3.1. Concentration changes according to language conditions

Figure 2 shows the mean HbO and HbR concentration changes in response to each of the language conditions across channels, for all newborns averaged together (see SI, Table S1 for a statistical summary of the results).

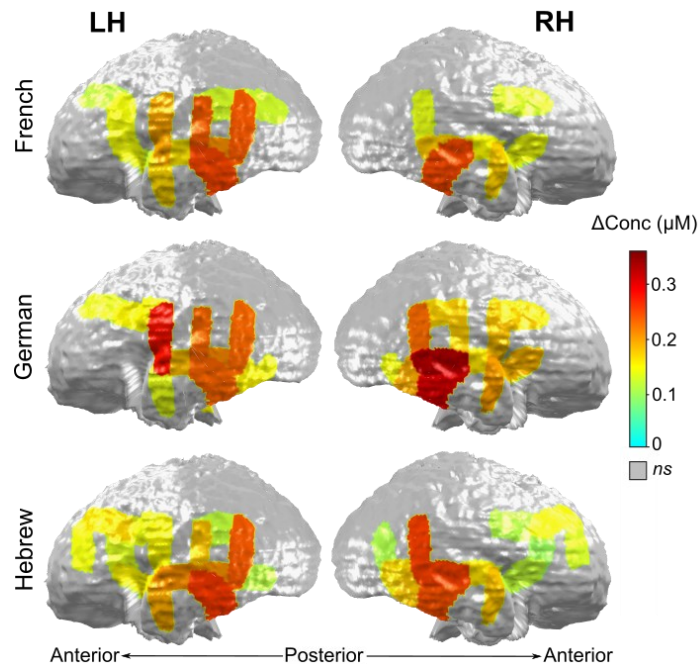


**Figure 2.** Grand average hemodynamic concentration changes according to language conditions across all participants. Channels are plotted according to the cap placement shown in Figure 1. Channel identification numbers are indicated to the left of each plot. Full lines represent HbO, and dashed lines represent HbR (French in black, German in red, Hebrew in blue). Colored areas around the curves represent the standard error of the mean. The gray rectangle indicates the stimulation period from 0 to 15 sec. Significant HbO activations between 7 and 15 sec compared to the baseline are indicated with a colored asterisk (\*) ( $p < .05$  after FDR correction).

Compared to the silent baseline, a significant increase in HbO (see Figures 2 and 3) was found for all language conditions for channels located in the bilateral frontal, temporal, and temporo-parietal regions (refer to Figure 1c for channels and ROI distribution). In channels in the posterior region, we observed significant HbO concentration changes only in response to non-

native language conditions (i.e. German and Hebrew) but not for the French language condition. Overall, the native language condition generated a significant HbO increase in 19 channels, 12 within the LH and 7 within the RH. In comparison, we observed a total of 23 and 28 significant channels in response to the German and Hebrew stimuli, respectively, which were distributed evenly in both hemispheres (11 in the LH and 12 in the RH for German, 14 and 14 for Hebrew).

A significant decrease in HbR was found for all conditions for channels located in the bilateral temporal, temporo-parietal, and posterior regions (see Figure 2 and SI Figure S1). In channels located in the frontal region, we observed a significant HbR decrease only in response to French and Hebrew, while for the German language condition, there were no significant channels in this region in either hemisphere. The Hebrew condition generated the most diffuse HbR concentration changes with 18 channels in the LH and 17 channels in the RH showing a significant HbR decrease. In comparison, we observed 11 significant channels in the LH and 8 in the RH for French, and 7 and 7 for German.

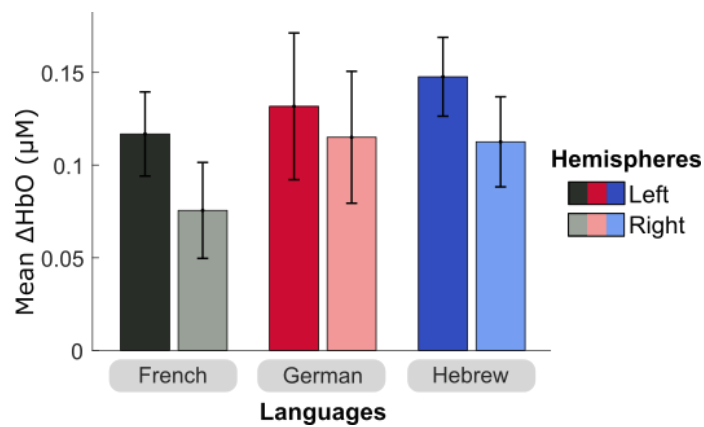


**Figure 3.** Topographical representation of mean HbO concentration changes between 7 and 15 sec after stimulus onset according to language condition. Only significant channels are displayed in color ( $p < .05$  after FDR adjustment).

### 3.2. The influence of prenatal experience on hemodynamic responses

#### 3.2.1. Frontal region

The ANOVA for HbO, with the between-subject factor *Group* and the within-subject factors *Language* and *Hemisphere*, revealed a main effect of *Hemisphere* ( $F_{1,47} = 7.08$ ,  $p = .042$ ,  $\eta_p^2 = 0.131$ ), due to larger concentration changes in the LH than in the RH (Figure 4). This effect was independent of other factors, suggesting that the left hemispheric dominance was similar across groups and language conditions. There was no other main effect or interaction that reached a level of significance (all  $ps > .05$ ).



**Figure 4.** Statistically significant HbO left hemispheric asymmetry in the frontal region, averaged across all participants. Darker colors represent the LH, and lighter colors represent the RH, for each language condition (French in black, German in red, Hebrew in blue). Error bars represent standard error of the mean.

#### 3.2.2. Temporal and posterior regions

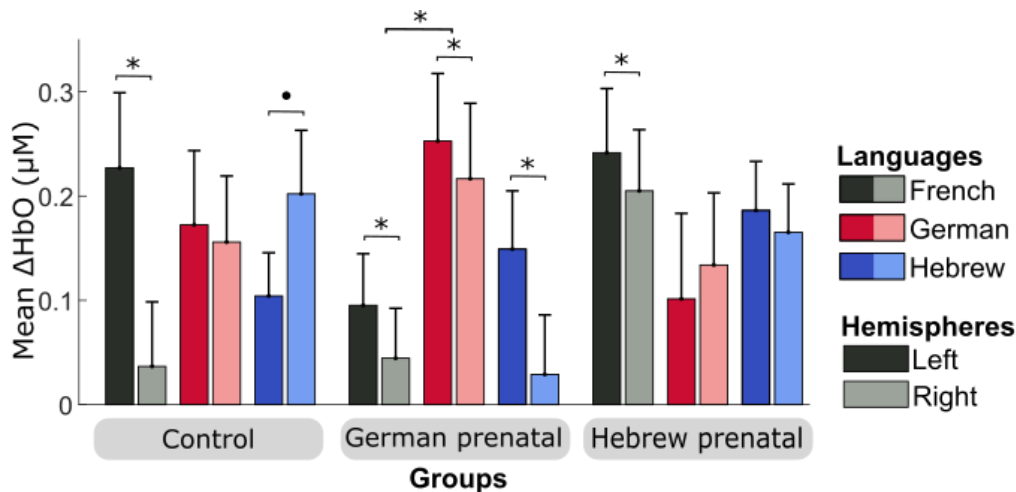
The ANOVA yielded no significant main effect or interaction for HbO in either the temporal region or the posterior region (all  $ps > .05$ ).

#### 3.2.3. Temporo-parietal region

The interaction between *Group*  $\times$  *Language*  $\times$  *Hemisphere* reached significance ( $F_{4,94}=3.70$ ,  $p = .038$ ,  $\eta_p^2 = 0.136$ ; Figure 5). There was no other main effect or interaction (all  $ps > .05$ ). To understand the temporo-parietal triple interaction, separate ANOVAs were first conducted for each language with *Hemisphere* and *Group* as factors. For French, we found a significant main effect of

*Hemisphere* ( $F_{1,47}=8.25, p = .006, \eta_p^2 = 0.149$ ) due to a greater involvement of the LH in all three groups. For Hebrew, we observed an interaction between *Group*  $\times$  *Hemisphere* ( $F_{2,47}=4.05, p = .023, \eta_p^2 = 0.147$ ). Newborns in the German prenatal group showed a larger response in the LH than in the RH ( $p = .037$ ). No difference reached significance in the two other groups, even though the control group showed a trend towards a larger response in the RH than in the LH ( $p = .069$ ). For the German language condition, we found no significant effect or interaction.

To further assess how responses in the temporo-parietal region differed according to prenatal experience, separate ANOVAs were also conducted within each group with *Hemisphere* and *Language* as factors (Figure 5). In the control group, we found an interaction between *Language*  $\times$  *Hemisphere* ( $F_{2,34}=5.57, p = .008, \eta_p^2 = 0.247$ ) with a larger response in the LH than the RH to French stimuli ( $p = .010$ ), but not to German or Hebrew stimuli. In the German prenatal group, the main effects of *Hemisphere* ( $F_{1,15}=4.65, p = .048, \eta_p^2 = 0.236$ ) and *Language* ( $F_{2,30}=3.32, p = .049, \eta_p^2 = 0.181$ ) reached significance. The former was due to a larger response in the LH than in the RH, regardless of the language condition. The latter was the result of a larger response to German than to French stimuli ( $p = .045$ ). In the Hebrew prenatal group, no significant effect or interaction was observed.



**Figure 5.** Mean HbO concentration changes in the temporo-parietal region according to group, language condition (French in black, German in red, Hebrew in blue) and hemisphere (darker colors for the LH, lighter colors for the RH). Error bars represent standard error of the mean.

\*  $p < .05$  (statistically significant); •  $p < .07$  (statistical tendency)

Similar analyses applied to HbR concentration changes yielded no significant effect in any of the ROIs (all  $ps > .05$ ).

## **4. Discussion**

The current study investigated the brain responses to speech in familiar and unfamiliar languages in newborns. To understand how the prenatal linguistic environment modulates brain responses, two groups of newborns were repeatedly exposed to a story in their native language as well as in one of two unfamiliar languages during their last month of gestation. These two groups were compared to a control group with no experimental prenatal exposure. The non-native languages, German and Hebrew, were chosen because they are rhythmically different from the native language of French, but vary in their degree of similarity to French in regard to other phonological properties.

### ***4.1. Differential processing of the native language along the fronto-temporo-parietal network***

Our results revealed that speech processing at birth involved a fronto-temporo-parietal network with distinctive response patterns across hemispheres and regions according to language familiarity. Overall, the brain response to the native language appeared to be more left-lateralized than the response to the unfamiliar languages. Regardless of their prenatal exposure, all newborns displayed a left hemispheric advantage in the frontal area in response to both native and non-native languages, and in the temporo-parietal region for the native language only. Our findings therefore support the presence of an early left hemispheric specialization for the native language, already in place in the first hours after birth. This specialization was not modulated by a short prenatal exposure to a novel, non-native language.

Our evidence of a hemispheric asymmetry is in accordance with several other studies that highlighted an emerging left lateralization from birth in response to speech, both at the structural and functional level (Dehaene-Lambertz et al., 2010; Mercure et al., 2020; Minagawa-Kawai et al., 2011a, 2011b; Peña et al., 2003; Vannasing et al., 2016). When processing speech, newborns display a cerebral network that expands bilaterally but predominantly recruits left fronto-temporal regions, as was indeed observed in our study for the native language. This leftward advantage in the language network is observed in several processes from birth, such as the detection of linguistic structure (Bouchon et al., 2015; Gervain et al., 2008), learning and recognition of speech stimuli (Benavides-Varela et al., 2017; Benavides-Varela & Gervain, 2017), differentiation

of the native from unfamiliar languages (Sato et al., 2012; Vannasing et al., 2016), and identification of the communicative functionality of speech (Forgács et al., 2022). Nonetheless, as the infant develops and gains language experience, its brain activation is known to gradually become more focalized and lateralized in response to its native language in contrast to an unfamiliar language (e.g. Cristia et al., 2014; Minagawa-Kawai et al., 2011a; Sato et al., 2010). However, the degree of hemispheric asymmetry in regard to language experience may vary depending on the cerebral region. For instance, a study with preverbal infants aged from 4 to 8 months observed that while all displayed a left hemispheric advantage in the frontal region, the hemispheric specialization in the posterior temporal region varied accordingly of the infant's monolingual or bilingual experience (Mercure et al., 2020). Taken together with our study, this body of evidence suggests that the temporo-parietal region is tuned, even from birth, to the native language and is therefore particularly relevant to experience-dependent learning in prenatal and early language development.

#### ***4.2. Language familiarity and phonological features both modulate speech processing***

A key finding of our study is that the experimental manipulation of infants' prenatal experience, through repeated exposure to a new language, triggered a differentiated response in the temporo-parietal regions. In contrast to the left hemispheric advantage observed for the native language, the three groups showed different brain response patterns to them in the temporo-parietal regions. This indicates that language processing at birth is shaped by prenatal experience. However, the German- and Hebrew-exposed groups did not respond to their familiarized non-native language in the same way.

Specifically, newborns exposed prenatally to German showed a left hemispheric asymmetry in response to all three languages, while the control and Hebrew-exposed newborns responded with a left hemispheric advantage to the native language only. The left hemispheric specialization not only to the native language but also to the prenatally-familiarized and unfamiliar non-native languages in the German-exposed group may reflect an increased efficiency in the way these newborns process familiar and novel speech stimuli (Mills et al., 2005). As mentioned previously, the left hemisphere is known to be predominantly recruited in verbal memory and learning from birth (Benavides-Varela et al., 2017; Bouchon et al., 2015; Minagawa-Kawai et al., 2011a). The prenatal German-exposed group also displayed greater activation in response to the familiarized



German stimuli than to the familiarized French stimuli. While there are very few studies that have used prenatal experimental manipulation, Partanen and colleagues (2013b) have also observed an enhanced cerebral response to acoustical stimuli that were experienced repeatedly during the prenatal period. Even though both the French and German stimuli were familiar, due to repeated exposure during the prenatal period, French was the native language in our sample, the language mothers spoke during gestation. This indicates that, although relatively short, the prenatal exposure to German might have been enough for neonates to recognize the German stimuli as familiar, while still discriminating it from the very familiar native language.

Contrary to the German prenatal group, Hebrew-exposed newborns showed no difference in HbO response between language conditions and no hemispheric lateralization for Hebrew. This may suggest that the neural mechanisms of speech processing at birth are not solely influenced by familiarity, but also by the phonological features of the languages themselves. While German and Hebrew are both stress-timed and French is syllable-timed, those rhythmic categories do not cover the full complexity of phonological and rhythmic variability across languages (Arvaniti & Rodriguez, 2013; Gasparini et al., 2021; Nespor, 1990). With respect to several other phonological properties, Hebrew and French are more similar to each other than are German and French. Both Hebrew and French typically use iambic patterns (Bijeljic-Babic et al., 2012; Nazzi et al., 2006; Segal et al., 2015), which is markedly different from the typical trochaic lexical stress in German (Höhle et al., 2009). Furthermore, German has greater syllabic complexity than French or Hebrew, and this results in a reduced rate of speech (Fenk-Oczlon & Fenk, 2010).

We may therefore speculate that the greater difference in rhythmic and phonological features between French and German might have facilitated experience-dependent learning prior to birth. Previous studies have found that greater variability in language stimuli modulates the behavioral and brain responses in several domains, such as rule learning and attention shifting (Bouchon et al., 2015; D'Souza et al., 2020; Gervain et al., 2008). Though our study cannot identify which language features may promote *in utero* learning or are being preferentially responded to at birth, a potential hypothesis is that pitch and speech rate might, since these acoustic characteristics did differ across our linguistic stimuli. These differences represent a natural variation that is intrinsic to the phonology of the chosen languages, even when spoken by the same multilingual speaker (Lee & Sidtis, 2017; Zimmerer et al., 2014). Specifically, German stimuli had a slower

speech rate than the other two languages, because of its higher syllabic complexity (Arvaniti & Rodriquez, 2013; Fenk-Oczlon & Fenk, 2010). It also displayed a higher mean pitch than French and Hebrew. Pitch varies across languages, as it serves different linguistic and meta-linguistic functions in different languages (Nespor, 1990; Nespor & Vogel, 1986). Newborns and infants have been shown to be highly sensitive to pitch patterns and speech rate (Abboub et al., 2016; Chong et al., 2018; Nazzi et al., 1998b; Song et al., 2010). Therefore, the difference between our language stimuli, in relation to) these two variables, might have made it easier to discriminate the German stimuli from the French ones, for those infants who had been familiarized to this language.

Finally, the response pattern within the control group might also be suggestive of a cumulated influence between language familiarity and phonological features. Newborns in this group had not been exposed to either of the foreign languages during gestation and were therefore only familiar with French, their native language. While the native language induced a clear left hemispheric asymmetry in temporo-parietal regions, the two unfamiliar languages triggered an activation of similar amplitude in both hemispheres. Likewise, other newborn studies have found bilateral responses to unfamiliar languages (May et al., 2011, 2017; Sato et al., 2012). Nonetheless in our study, marginally greater activation was observed in the right than in the left hemisphere in response to Hebrew. This pattern is consistent with results obtained by Vannasing and colleagues (2016), who found a right dominant activation in response to the unfamiliar language (i.e. Arabic), and a left lateralized response to the French native language. Taken together, these studies suggest that processing foreign languages may elicit distinctive hemispheric dominance patterns according to these languages' specific sound patterns. Our study highlights the need to consider not only the familiarity, but also the linguistic and phonological properties of the languages tested within a study.

### ***4.3. Limitations***

This study has several limitations that must be acknowledged. First, even if a substantial number of participants took part in our study overall, sample sizes were modest for each subgroup included in our final analyses. Moreover, when designing this study, we opted not to include comparable non-linguistic conditions (e.g. reversed speech, complex melody) due to the limited acquisition time possible for newborns, and because distinctive patterns in response to these stimuli have already been well documented (May et al., 2011, 2017; Minagawa-Kawai et al., 2011b; Peña et al.,

2003; Sato et al., 2012; Vannasing et al., 2016). Our paradigm allowed us to instead have two unfamiliar language conditions, enabling us to test not only the role of familiarity but also the contributions of specific sound patterns in different languages. It also allowed us to optimize the signal-to-noise ratio by increasing the number of trials within each condition, compared to other fNIRS neonatal and infant studies (e.g. Abboub et al., 2016; Bartha-Doering et al., 2019; May et al., 2017; Mercure et al., 2020), as an insufficient number of valid trials in the final analyses is a common issue in infant imaging studies (Vanderwert & Nelson, 2014).

In order to match the acoustic characteristics of each language stimuli as closely as possible to each other, we chose one multilingual female speaker to record the stimuli in each of the three languages. Except for the normalization of stimulus intensity, no other acoustic parameter was manipulated. The relative contribution of specific phonological features could therefore not be tested. Languages have inherent differences in their phonological features, even when spoken by the same multilingual speaker (Lee & Sidtis, 2017; Zimmerer et al., 2014). Similar to Vannasing and colleagues (2016), we decided to use naturalistic speech instead of experimentally manipulating specific acoustic features, such as low-pass filtering (e.g. May et al., 2011), in order to preserve the ecological validity of the stimuli. This, however, increased the difference between how our participants heard the stimuli while *in utero* (i.e. naturally low-pass filtered) and as presented after birth, which might have thus hindered its recognition after birth.

Further research directly targeting specific linguistic features will be necessary to disentangle the contributions of different phonological properties to speech processing, perinatal learning, and the emergence of hemispheric specialization for language processing. As suggested above, rhythmic and phonological features such as speech rate and pitch may be compelling candidates for promoting language learning and recognition, notably because prosody is one of the key language features preferentially processed in the right hemisphere (e.g. Homae et al., 2006; Martinez-Alvarez et al., 2022; Telkemeyer et al., 2009), and is considered of utmost importance in early language acquisition (Abboub et al., 2016; Fló et al., 2019; Nazzi et al., 1998a). Nonetheless, speech is a dynamically changing and complex auditory signal that contains information at several frequency and temporal scales, and its features can be analysed in association with neural oscillations (Poeppel, 2014). Combining electrophysiology simultaneously with hemodynamic

measurements is an interesting potential avenue to track the temporal and spatial patterns of neural responses in relation to speech properties (e.g. Cabrera & Gervain, 2020; Wallois et al., 2012).

## **5. Conclusion**

Our study demonstrates that even a short *in utero* exposure to an unfamiliar language can influence speech processing and may facilitate language discrimination at birth. This experience-dependent modulation of the brain response was located close to the posterior part of the superior temporal gyrus and the inferior parietal area, which are key regions involved in language processing. Furthermore, newborns' brain responses differed according to the phonological properties of the non-native language to which they were exposed prenatally. This suggests that while speech processing at birth is shaped through prenatal experience, the specific characteristics of different languages may also play a role in their neural processing. Finally, our results are in line with existing findings about the emergence, while *in utero*, of a left hemispheric specialization for the native language. Our study shows that this lateralization is not affected by a relatively short prenatal exposure to another language. Taken together, our findings support the idea that the familiarity originating from the prenatal linguistic environment, and the phonological properties of languages both come into play and interact to shape language networks in the brain during early perinatal development.

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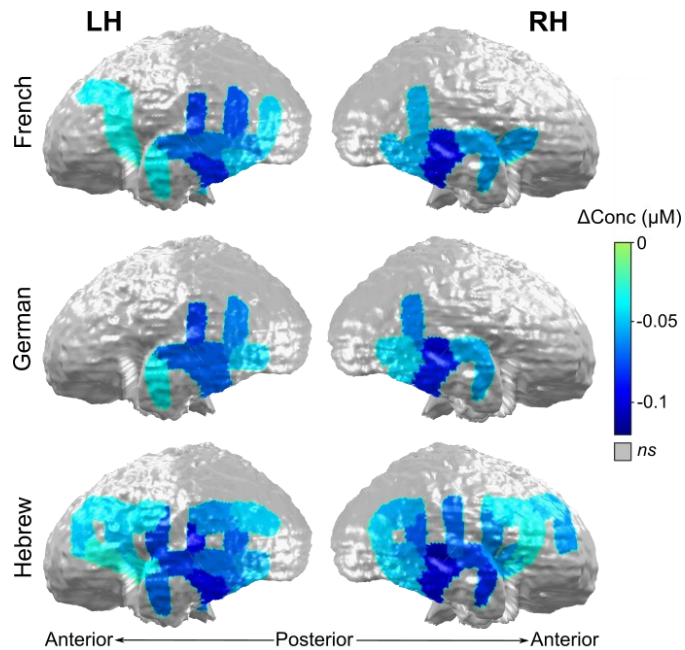
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## Supplementary information

*Channel selection for ROI analyses.* Channels included for the ROI analyses of variance are presented below (see Figure 1C for reference). For the frontal region, channels 1, 2, 4, 6, 7, and 9 were averaged together in the left hemisphere (LH), while channels 37, 39, 40, 42, 44, and 46 were averaged together in the right hemisphere (RH). Regarding the temporal region, the LH regrouped channels 10, 12, 15, and 16, while the RH regrouped channels 32, 33, 36, and 38. In the temporo-parietal region, channels 13, 14, 17, and 18 were averaged together in the LH, and channels 25, 30, 31, and 34 were averaged together in the RH. Finally, for the posterior region, the LH regrouped channels 19, 20, 21, and 23, while the RH regrouped channels 24, 26, 27, and 28.



**Figure S1.** Topographical representation of mean HbR concentration changes during the time analysis period from 7 to 15 sec after stimulus onset. Only significant channels are displayed in color ( $p < .05$  after FDR adjustment).



**Table S1. Channel HbO and HbR concentration changes according to language conditions**

	French				German				Hebrew			
	HbO		HbR		HbO		HbR		HbO		HbR	
	T (df)	p	T (df)	p	T (df)	p	T (df)	p	T (df)	p	T (df)	p
<b>Frontal</b>												
<b>LH</b>												
ch1	1.46 (51)	0.991	-1.57 (51)	0.824	1.98 (51)	0.404	-1.86 (51)	0.511	4.20 (51)	0.002 **	-3.33 (51)	0.024 *
ch2	3.76 (51)	0.007 **	-3.42 (51)	0.019 *	3.08 (51)	0.037 *	-1.81 (51)	0.546	5.43 (51)	<0.01 ***	-3.20 (51)	0.031 *
ch3	1.68 (52)	0.682	-2.38 (51)	0.193	1.79 (52)	0.572	-0.33 (51)	1	2.87 (52)	0.061	-4.28 (51)	0.003 **
ch4	4.98 (50)	<0.01 ***	-3.26 (52)	0.028 *	2.73 (50)	0.083	-1.54 (52)	0.864	4.08 (50)	0.003 **	-4.93 (52)	<0.01 ***
ch5	1.78 (49)	0.572	-1.22 (50)	1	1.21 (49)	1	1.86 (50)	0.515	1.13 (49)	1	-0.57 (50)	1
ch6	2.28 (50)	0.223	-2.54 (52)	0.138	3.33 (50)	0.021 *	-2.45 (52)	0.168	4.03 (50)	0.003 **	-3.01 (52)	0.044 *
ch7	3.79 (50)	0.006 **	-1.70 (49)	0.672	2.45 (50)	0.160	-1.12 (49)	1	4.52 (50)	0.001 **	-3.11 (49)	0.037 *
ch9	4.08 (51)	0.003 **	-2.91 (52)	0.057	4.20 (51)	0.002 **	-2.84 (52)	0.065	4.51 (51)	0.001 **	-3.70 (52)	0.009 **
<b>RH</b>												
ch37	2.32 (49)	0.205	-2.91 (50)	0.057	3.49 (49)	0.014 *	-1.26 (50)	1	2.13 (49)	0.306	-3.33 (50)	0.024 *
ch39	3.50 (48)	0.014 *	-2.00 (48)	0.400	3.46 (48)	0.015 *	-1.92 (48)	0.468	3.13 (48)	0.034 *	-3.54 (48)	0.014 *
ch40	3.63 (49)	0.010 **	-4.20 (49)	0.003 **	4.13 (49)	0.003 **	-2.83 (49)	0.068	3.22 (49)	0.027 *	-4.81 (49)	0.001 **
ch42	2.08 (49)	0.335	-1.08 (50)	1	2.87 (49)	0.061	-1.44 (50)	1	3.69 (49)	0.008 **	-3.11 (50)	0.037 *
ch43	2.27 (48)	0.229	-2.41 (48)	0.185	0.82 (48)	1	-1.63 (48)	0.757	1.81 (48)	0.554	-2.95 (48)	0.054
ch44	1.03 (50)	1	-2.08 (50)	0.349	1.88 (50)	0.490	-2.19 (50)	0.277	4.78 (50)	<0.01 ***	-3.60 (50)	0.012 *
ch45	0.78 (49)	1	-0.78 (50)	1	1.64 (49)	0.735	-1.29 (50)	1	1.56 (49)	0.830	-2.35 (50)	0.205
ch46	0.61 (51)	1	-1.33 (52)	1	1.67 (51)	0.691	-2.13 (52)	0.313	3.95 (51)	0.004 **	-3.13 (52)	0.036 *
<b>Temporal</b>												
<b>LH</b>												
ch8	1.57 (50)	0.819	-0.10 (49)	1	0.17 (50)	1	1.84 (49)	0.524	0.35 (50)	1	0.16 (49)	1
ch10	4.26 (50)	0.002 **	-3.20 (51)	0.031 *	3.08 (50)	0.037 *	-3.08 (51)	0.038 *	4.49 (50)	0.001 **	-4.21 (51)	0.003 **
ch12	4.04 (47)	0.003 **	-4.20 (50)	0.003 **	3.84 (47)	0.006 **	-4.15 (50)	0.003 **	6.40 (47)	<0.01 ***	-4.66 (50)	0.001 **
ch15	4.89 (50)	<0.01 ***	-3.74 (52)	0.009 **	4.99 (50)	<0.01 ***	-5.16 (52)	<0.01 ***	4.54 (50)	0.001 **	-4.82 (52)	<0.01 ***
ch16	5.36 (50)	<0.01 ***	-4.46 (50)	0.002 **	4.81 (50)	<0.01 ***	-4.46 (50)	0.002 **	6.16 (50)	<0.01 ***	-5.47 (50)	<0.01 ***
<b>RH</b>												
ch32	4.59 (52)	<0.01 ***	-6.64 (51)	<0.01 ***	5.84 (52)	<0.01 ***	-4.69 (51)	0.001 **	5.63 (52)	<0.01 ***	-5.09 (51)	<0.01 ***
ch33	5.83 (51)	<0.01 ***	-6.89 (51)	<0.01 ***	5.64 (51)	<0.01 ***	-4.12 (51)	0.003 **	6.42 (51)	<0.01 ***	-7.31 (51)	<0.01 ***
ch36	3.84 (51)	0.006 **	-4.62 (50)	0.001 **	3.91 (51)	0.005 **	-3.90 (50)	0.006 **	4.38 (51)	0.001 **	-4.44 (50)	0.002 **
ch38	3.95 (51)	0.004 **	-4.47 (49)	0.002 **	3.54 (51)	0.012 *	-4.10 (49)	0.003 **	4.41 (51)	0.001 **	-5.12 (49)	<0.01 ***
ch41	0.66 (47)	1	-0.16 (49)	1	1.04 (47)	1	2.36 (49)	0.205	-0.15 (47)	1	-0.35 (49)	1
<b>Temporo-Parietal</b>												
<b>LH</b>												
ch11	1.32 (51)	1	-1.52 (51)	0.897	2.92 (51)	0.055	-1.64 (51)	0.748	2.34 (51)	0.200	-2.49 (51)	0.154
ch13	4.87 (52)	<0.01 ***	-4.30 (51)	0.003 **	4.47 (52)	0.001 **	-4.01 (51)	0.004 **	4.01 (52)	0.003 **	-4.69 (51)	0.001 **
ch14	3.07 (49)	0.038 *	-2.00 (50)	0.400	2.87 (49)	0.061	-1.84 (50)	0.524	4.30 (49)	0.002 **	-4.30 (50)	0.031 *
ch17	5.05 (52)	<0.01 ***	-4.17 (50)	0.003 **	4.09 (52)	0.003 **	-3.72 (50)	0.009 **	6.15 (52)	<0.01 ***	-4.91 (50)	<0.01 ***
ch18	3.21 (50)	0.027 *	-2.34 (50)	0.208	2.50 (50)	0.145	-2.29 (50)	0.233	2.27 (50)	0.226	-4.28 (50)	0.003 **
<b>RH</b>												
ch25	2.38 (49)	0.184	-2.26 (50)	0.244	2.05 (49)	0.355	-2.22 (50)	0.263	2.80 (49)	0.072	-4.15 (50)	0.003 **
ch30	3.28 (52)	0.023 *	-3.87 (52)	0.006 **	5.06 (52)	<0.01 ***	-4.38 (52)	0.002 **	5.45 (52)	<0.01 ***	-3.84 (52)	0.007 **
ch31	1.86 (51)	0.502	-0.84 (51)	1	4.07 (51)	0.003 **	-2.00 (51)	0.400	2.86 (51)	0.061	-1.69 (51)	0.684
ch34	1.45 (51)	0.991	-1.76 (52)	0.600	3.36 (51)	0.019 *	-2.66 (52)	0.101	2.18 (51)	0.269	-3.26 (52)	0.028 *
ch35	1.61 (51)	0.762	-0.17 (51)	1	1.94 (51)	0.428	-1.96 (51)	0.427	2.52 (51)	0.137	-0.85 (51)	1
<b>Posterior</b>												
<b>LH</b>												
ch19	0.94 (51)	1	-3.58 (52)	0.012 *	2.48 (51)	0.150	-3.11 (52)	0.037 *	3.34 (51)	0.020 *	-4.47 (52)	0.002 **
ch20	1.42 (50)	1	-3.33 (50)	0.024 *	3.71 (50)	0.008 **	-2.77 (50)	0.078	2.81 (50)	0.070	-4.24 (50)	0.003 **
ch21	1.41 (52)	1	-2.27 (51)	0.239	3.04 (52)	0.040 *	-1.87 (51)	0.511	2.95 (52)	0.051	-3.17 (51)	0.033 *
ch22	0.03 (50)	1	-2.06 (48)	0.359	2.38 (50)	0.184	0.51 (48)	1	0.55 (50)	1	-0.24 (48)	1
ch23	2.01 (52)	0.376	-3.72 (51)	0.009 **	1.36 (52)	1	-1.63 (51)	0.748	2.03 (52)	0.368	-2.90 (51)	0.057
<b>RH</b>												
ch24	1.29 (50)	1	-1.59 (49)	0.802	1.41 (50)	1	-1.14 (49)	1.623	3.21 (50)	0.027 *	-4.40 (49)	0.002 **
ch26	2.24 (49)	0.238	-2.87 (50)	0.062	2.77 (49)	0.075	-3.08 (50)	0.038 *	4.64 (49)	<0.01 ***	-3.91 (50)	0.006 **
ch27	2.58 (49)	0.120	-3.06 (49)	0.040 *	3.22 (49)	0.027 *	-2.21 (49)	0.269	4.39 (49)	0.001 **	-3.26 (49)	0.028 *
ch28	2.38 (50)	0.184	-3.81 (50)	0.007 **	4.86 (50)	<0.01 ***	-3.10 (50)	0.037 *	5.23 (50)	<0.01 ***	-3.56 (50)	0.013 *
ch29	-1.68 (48)	0.682	0.18 (48)	1	1.76 (48)	0.592	-0.07 (48)	1	1.34 (48)	1	0.56 (48)	1

*Note.* Channel numbers are displayed in the left column (see Figure 1C for reference). Student-*t* value (T) from paired test of the mean hemodynamic concentration change during the time window analysis compared to baseline level (degrees of freedom in parenthesis). *P*-values with FDR correction.

\*\*\*  $p < .001$ , \*\*  $p < .01$ , \*  $p < .05$

# Appendice

## Spécialisation et intégration hémisphérique

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<sup>1</sup> Disponible en ligne au <https://www.universalis.fr/encyclopedie/specialisation-et-integration-interhemispherique/>

C'est aux neurologues Marc Dax et Paul Broca vers le milieu du XIX<sup>e</sup> siècle que nous attribuons les premières découvertes liées à la spécialisation hémisphérique cérébrale (Tzourio-Mazoyer & Seghier, 2016). En observant des patients présentant des lésions cérébrales dans l'hémisphère gauche et des difficultés langagières importantes, ces médecins ont postulé la théorie de la dominance cérébrale de l'hémisphère gauche pour le langage. Ainsi, les premières connaissances portant sur la spécialisation et l'intégration interhémisphérique provenaient d'études de cas de patients avec une lésion cérébrale latéralisée ou dont le corps calleux était sectionné, ce qui empêche la communication entre les deux hémisphères du cerveau (Gazzaniga, 2000). D'autres méthodes, telles que le test de Wada et la stimulation intracrânienne, sont également utilisées sur une base clinique pour investiguer le rôle de chaque hémisphère dans les fonctions cérébrales (Bauer et al., 2014; Dym et al., 2011; Zumsteg & Wieser, 2000). Par ailleurs, l'arrivée révolutionnaire de l'imagerie cérébrale fonctionnelle (principalement l'imagerie par résonance magnétique fonctionnelle, IRMf) a engendré une augmentation exponentielle des études scientifiques sur le sujet depuis les années 1990 (Bradshaw et al., 2017; Concha et al., 2012; Herve et al., 2013), ce qui a permis de grandement faire avancer notre compréhension de la spécialisation et de l'intégration interhémisphérique, et ce, tant chez les patients que chez les individus neurologiquement sains.

## **1. Spécialisation et intégration : définitions**

La spécialisation hémisphérique cérébrale reflète l'hébergement de réseaux neuronaux spécialisés dans une fonction cognitive ou comportementale par un hémisphère cérébral (Herve et al., 2013). Le terme *spécialisation hémisphérique* a graduellement remplacé le terme *latéralisation cérébrale*, autrefois beaucoup plus répandu, pour tenir compte de la nuance selon laquelle les deux hémisphères travaillent conjointement et que les fonctions ne sont pas strictement prises en charge par un seul hémisphère (Banich, 2009). Cette nuance s'est notamment développée de pair avec l'avancement des méthodes d'investigation, qui permettent aujourd'hui une meilleure précision et compréhension du fonctionnement cérébral. D'autres termes sont également rencontrés dans les écrits scientifiques, notamment la *dominance hémisphérique* et l'*asymétrie cérébrale*. L'*intégration interhémisphérique* réfère quant à elle à l'interaction entre les hémisphères des réseaux neuronaux spécialisés permettant un traitement de l'information plus rapide et efficace (Sporns, 2013; van der Knaap & van der Ham, 2011; Wang et al., 2014) optimisant ainsi le

fonctionnement cérébral (Corballis & Badzakova-Trajkov, 2012). Il faut savoir que la spécialisation et l'intégration interhémisphérique ne sont pas des propriétés propres au cerveau humain, étant notamment observées chez les primates (Iturria-Medina et al., 2011), les souris (Ehret, 1987; Ma et al., 2018) et les oiseaux chanteurs (Cynx et al., 1992).

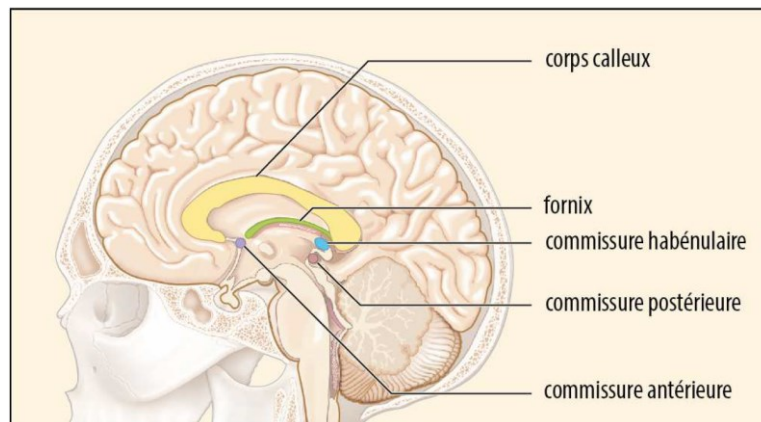
Une conception populaire de la spécialisation hémisphérique du cerveau est que les individus aient un cerveau droit dominant s'ils sont créatifs ou un cerveau gauche dominant s'ils sont rationnels (Corballis, 2014). Cela est toutefois un mythe : la spécialisation hémisphérique varie selon les fonctions cognitives recrutées et tâches effectuées et non selon les individus et leur personnalité (Nielsen et al., 2013). L'asymétrie cérébrale change ainsi selon les régions à même un cerveau, et l'organisation hémisphérique cérébrale est relativement similaire entre les individus (Chiarello et al., 2016; Kong et al., 2018; Nielsen et al., 2013).

La spécialisation et l'intégration interhémisphérique sont étroitement reliées. Un nombre restreint de régions cérébrales habituellement localisées dans un seul hémisphère est recruté pour effectuer des tâches simples (Bradshaw et al., 2017; van der Knaap & van der Ham, 2011). Plus la complexité de la tâche et du traitement requis augmente, plus les régions cérébrales recrutées sont nombreuses et s'étendent aux deux hémisphères (Bradshaw et al., 2017; Welcome & Chiarello, 2008), indiquant ainsi une augmentation de la coopération et de l'intégration interhémisphérique (Sporns, 2013). Ainsi, le degré de latéralisation des différentes fonctions cérébrales peut significativement varier selon la performance, la difficulté et le type de tâche.

## **2. Connectivité et intégration interhémisphérique par le corps calleux**

Pour permettre l'intégration interhémisphérique, les différentes populations neuronales localisées dans les deux hémisphères doivent pouvoir communiquer entre elles. Les groupes de neurones qui travaillent ensemble s'organisent généralement en réseaux qui permettent la spécialisation de fonctions (Bullmore & Sporns, 2009). Ces différents réseaux neuronaux s'interchangent de l'information en permanence, ce qui permet l'intégration cérébrale. Les corps cellulaires des neurones, qui constituent la matière grise du cerveau, communiquent continuellement ensemble par le biais des axones, qui constituent la matière blanche. Pour permettre l'intégration cérébrale, les axones des neurones d'un réseau se regroupent pour former des faisceaux de matière blanche et connecter différentes régions cérébrales (voir Figure 1).

Certains faisceaux, dont le faisceau arqué et le faisceau unciné, permettent la connexion entre des régions situées dans un même hémisphère (communication intrahémisphérique). D'autres faisceaux, comme le corps calleux et les commissures antérieures et postérieures, assurent la connexion interhémisphérique entre des régions, souvent homologues (« miroirs »), localisées dans les hémisphères gauche et droit (voir Figure 2).

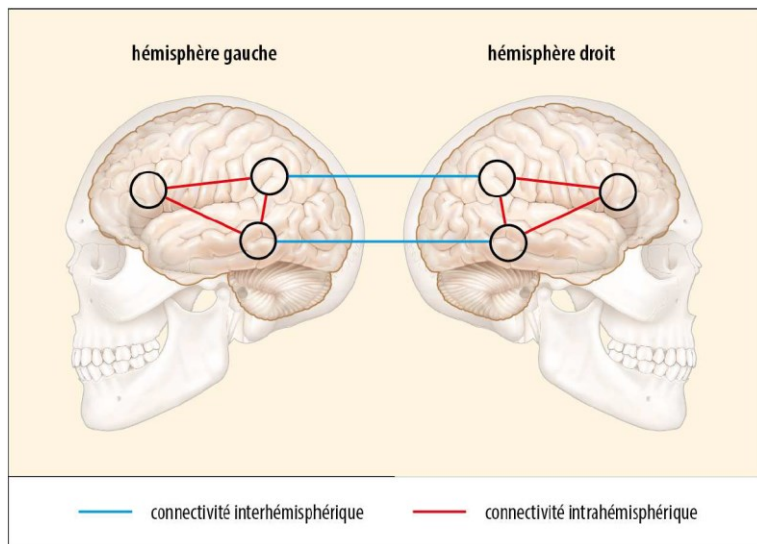


*Crédits : Encyclopædia Universalis France*

**Figure A1.** Représentation des principales commissures interhémisphériques du cerveau. Les principales commissures interhémisphériques du cerveau sont le corps calleux, le fornix et les commissures habénulaire, postérieure et antérieure. Ces faisceaux de matière blanche permettent la communication entre les régions homologues des hémisphères gauche et droit.

Le corps calleux est le faisceau interhémisphérique le plus important, autant par sa grosseur que par sa fonctionnalité (Aboitiz & Montiel, 2003). Il a principalement été étudié chez les patients callosotomisés, soit ceux qui ont un sectionnement partiel ou complet de leur corps calleux, réduisant significativement la communication et l'intégration interhémisphérique de l'information (Ouimet, 2010). Deux fonctions en quelque sorte contradictoires, mais ayant chacune reçu un support scientifique, sont attribuées au corps calleux (Badzakova-Trajkov, 2016; Sporns, 2013; van der Knaap & van der Ham, 2011). D'une part, le corps calleux pourrait inhiber le message provenant des régions homologues à l'hémisphère qui est recruté dans la tâche, ce qui permettrait une réduction de l'interférence et un traitement plus efficace. Sa fonction inhibitrice permettrait ainsi de préserver la spécialisation hémisphérique. D'autre part, le corps calleux pourrait aussi avoir une fonction excitatrice alors qu'une région activée lors d'une tâche susciterait l'activation de sa région homologue par l'intermédiaire du corps calleux. Cela permettrait un partage du traitement

de l'information favorisant l'intégration interhémisphérique (Steinmann et al., 2018). En fait, il est fort probable que le corps calleux soit à la fois excitateur et inhibiteur : il serait modulé en fonction de la nature et de la complexité de l'information à traiter ou de la tâche à accomplir (Bloom & Hynd, 2005; Roland et al., 2017). Néanmoins, d'autres études sont requises pour approfondir notre compréhension de son fonctionnement.



*Crédits : Encyclopædia Universalis France*

**Figure A2.** Schématisation de la connectivité intra- et interhémisphérique dans le cerveau. La connectivité intrahémisphérique représente les connexions entre les régions situées dans un même hémisphère, alors que les connexions entre les deux hémisphères cérébraux correspondent à la connectivité interhémisphérique. Ces connexions peuvent être conceptualisées comme étant structurelles et également fonctionnelles. La connectivité structurelle réfère aux liens anatomiques entre diverses régions cérébrales, tandis que la connectivité fonctionnelle représente l'activation synchrone de certaines régions. Par exemple, des régions impliquées dans le décodage de symboles visuels et le langage pourraient généralement s'activer conjointement lorsqu'une personne doit lire un texte.

### 3. Spécialisation hémisphérique spécifique à diverses fonctions

Plusieurs fonctions cérébrales, notamment le langage, le traitement musical, les fonctions visuospatiales, la mémoire, les habiletés mathématiques et le contrôle moteur, sont étudiées dans le contexte de la spécialisation hémisphérique (Herve et al., 2013; Tzourio-Mazoyer & Seghier, 2016). Certaines théories estiment que la dominance hémisphérique de certaines fonctions « pousserait » d'autres fonctions à être prises en charge par l'hémisphère controlatéral (opposé)

afin d'éviter l'encombrement (Herve et al., 2013). Par exemple, la dominance à gauche associée au langage engendrerait une dominance hémisphérique droite pour les habiletés visuospatiales (Cai et al., 2013). D'autres théories proposent plutôt que la distribution hémisphérique des fonctions provient de facteurs biologiques indépendants, et qu'ainsi, la spécialisation hémisphérique du langage et des habiletés visuospatiales se développe relativement indépendamment et simultanément (Badzakova-Trajkov, 2016; Rosch et al., 2012). Ces théories ont toutes deux des appuis scientifiques et davantage d'études sont nécessaires pour comprendre l'origine et le développement de la spécialisation.

### ***3.1. Langage***

Le langage est probablement la fonction la plus étudiée en termes de latéralisation cérébrale. Il est connu que 90 à 94 % des individus présentent une dominance langagière hémisphérique à gauche (Dehaene-Lambertz, 2017; Friederici et al., 2011; Tzourio-Mazoyer et al., 2017). La dominance manuelle est vue comme un facteur de variabilité important au niveau de la distribution cérébrale des réseaux langagiers, mais approximativement 80 % des gauchers ont tout de même une dominance à gauche (Costanzo, 2015; Szaflarski et al., 2012). Ce taux est également plus bas dans certaines populations cliniques qui ont des troubles neurologiques, comme une épilepsie frontale ou temporale gauche (Gallagher, Tanaka, et al., 2012; Tzourio-Mazoyer et al., 2017). L'évaluation de la dominance hémisphérique du langage est ainsi obligatoire chez ces patients si une neurochirurgie est envisagée pour traiter l'épilepsie afin de s'assurer de préserver les fonctions langagières après l'intervention chirurgicale (Gallagher, Béland, et al., 2012).

Les régions cérébrales bien connues pour être typiquement recrutées lors de la production et la compréhension du langage sont respectivement les aires de Broca et de Wernicke, toutes deux nommées selon les neurologues qui les ont étudiées et associées à leur fonction respective (Price, 2010). Ces régions sont respectivement situées dans la région frontale inférieure gauche et la partie postérieure de la région temporale supérieure gauche du cerveau. Néanmoins, les réseaux langagiers englobent des régions bien plus larges au sein des deux hémisphères cérébraux (Poeppel et al., 2012). On observe toutefois une maturation de la spécialisation hémisphérique avec le développement (Emerson et al., 2016). Dès la naissance, la dominance à gauche est déjà présente (Peña et al., 2003; Vannasing et al., 2016), mais l'activation reste plus distribuée entre les deux hémisphères chez les nourrissons, comparativement au cerveau adulte duquel les régions

langagières à gauche communiquent étroitement entre elles (Skeide & Friederici, 2016). Par ailleurs, tant chez l'adulte que l'enfant, l'hémisphère droit est impliqué dans le traitement langagier (Friederici, 2013), notamment pour traiter les indices pragmatiques et prosodiques du langage (Homae et al., 2006; Lindell, 2006).

### ***3.2. Prosodie et musique***

La prosodie réfère aux indices non verbaux dans la parole, telles l'accentuation et l'intonation (Witteman et al., 2011). Le traitement des indices prosodiques du langage est associé à une activation dominante à droite, ce qui est très similaire au traitement de la mélodie dans la musique (Koelsch, 2011; Perani et al., 2010). Le traitement du langage et de la musique peuvent ainsi être mis en parallèle. Un autre exemple concerne la structure du langage (syntaxe de la phrase) et la structure mélodique (syntaxe musicale) qui sont toutes deux traitées par les régions frontales inférieures, mais avec une dominance gauche et droite respectivement (Koelsch, 2011; Oechslin et al., 2018). Ce même parallèle peut être fait entre l'identification des phonèmes dans la langue, traités à gauche, et des timbres dans la musique, traités à droite. Une des hypothèses proposées par les scientifiques (Zatorre & Gandour, 2007) stipule que l'hémisphère gauche serait spécialisé dans le traitement des informations avec un grand détail temporel (plus hautes fréquences), nécessaires lors de la segmentation de l'information phonétique, tandis que la mélodie et la prosodie requièrent plutôt une analyse de l'enveloppe des sons, soit les variations temporelles plus lentes, prise en charge par l'hémisphère droit.

### ***3.3. Traitement visuospatial et reconnaissance des visages***

Une autre fonction pour laquelle une spécialisation hémisphérique a été démontrée est le traitement visuospatial. Les stimuli présentés dans le champ visuel gauche sont perçus par l'hémisphère droit et vice versa (traitement controlatéral), comme c'est également le cas pour le contrôle moteur. Ainsi, l'hémisphère recruté pour la perception visuelle est dépendant de la position du stimulus dans l'espace. Toutefois, le traitement de plus haut niveau et l'intégration des informations visuelles et de leur localisation sont principalement sous-tendus par les régions pariétales et frontales de l'hémisphère droit, quelle que soit la position du stimulus (Wang et al., 2014). Par ailleurs, cette dominance à droite est aussi présente au niveau de l'attention spatiale, entraînant un biais spatial vers la gauche (Jewell & McCourt, 2000). En effet, lorsqu'un individu



doit tracer une ligne au centre d'un trait pour le séparer en deux parties égales, une légère déviation vers la gauche est généralement mesurée dans la population globale.

Au niveau du traitement et de la reconnaissance des visages, des activations occipitales et temporales bilatérales avec une dominance à droite sont rapportées dans les études scientifiques (Duchaine & Yovel, 2015; Toga & Thompson, 2003). Il semblerait néanmoins que le développement de cette spécialisation ne soit pas clair : les recherches chez les nourrissons supportent l'émergence hâtive de cette dominance, alors que les études chez les enfants et adolescents supportent l'émergence graduelle et plus tardive de la spécialisation à droite survenant conjointement avec l'apprentissage de la lecture (Dundas et al., 2013).

### ***3.4. Dissociation entre le traitement verbal et visuel***

Comme mentionné précédemment, les tâches langagières et visuospatiales sont principalement prises en charge par les hémisphères gauche et droit respectivement. En fait, on peut observer une certaine dissociation entre le traitement cérébral verbal et visuel pour diverses habiletés cognitives, telles l'attention, la mémoire de travail et la mémoire. Par exemple, l'activation cérébrale lors d'une tâche de mémoire de travail est dépendante de la modalité des informations à traiter : une tâche verbale engendre une activité frontale plus importante à gauche alors qu'une tâche visuospatiale recrute principalement le cortex frontal droit (Thomason et al., 2009). Par ailleurs, au niveau de la reconnaissance visuelle, les lettres et les chiffres seraient initialement traités de manière préférentielle par les hémisphères gauche et droit respectivement (Park et al., 2014). Toutefois, l'exécution de manipulations arithmétiques (par exemple, des calculs), soit un traitement de plus haut niveau que la perception visuelle, demeure supportée principalement par l'hémisphère gauche, comme pour le traitement langagier (Pinel & Dehaene, 2009). Ces dissociations et similarités dans le traitement des symboles linguistiques et non linguistiques est d'autant plus intéressante, car ceux-ci sont des formes arbitraires ayant une signification culturelle, montrant ainsi l'influence de l'apprentissage sur l'organisation cérébrale (Ansari & Dhital, 2006).

Un autre exemple intéressant à cet effet concerne les patients callosotomisés et le traitement des visages, lors d'une tâche impliquant la présentation de deux visages côte-à-côte (Levy et al., 1972). Lorsque la consigne était de décrire verbalement le visage perçu, une activation dominante

dans l'hémisphère gauche était observable et les patients décrivaient le visage présenté à droite. Au contraire, l'hémisphère droit était recruté lorsqu'ils avaient comme consigne de pointer un visage; ils pointaient alors celui situé à gauche. Ainsi, en fonction de la nature de la tâche et de la réponse requise, la distribution de l'activité cérébrale associée à des habiletés cognitives de plus haut niveau peut grandement varier, comme le montre cet exemple chez les patients dont les deux hémisphères ne peuvent échanger l'information.

#### **4. Conclusion**

Bien que le cerveau soit organisé de manière à ce que chaque hémisphère prenne en charge certaines fonctions de façon dominante, les études montrent une intégration interhémisphérique importante permettant une optimisation du fonctionnement cérébral (van der Knaap & van der Ham, 2011). La plasticité cérébrale est une propriété inhérente au cerveau et peut moduler la spécialisation et l'intégration interhémisphérique, par exemple en cas de lésion cérébrale. Des études chez des patients avec une tumeur cérébrale ont montré que dans certains cas, lorsque la tumeur progresse très lentement, la perte importante de tissu cérébral ne semble pas avoir d'impact au niveau des habiletés cognitives, mais entraîne néanmoins une réorganisation cérébrale importante (Keidel et al., 2010). Par exemple, on peut observer un transfert du traitement du langage vers l'hémisphère droit dans les cas de tumeurs à gauche, ce qui peut également être le cas chez des individus avec une épilepsie fronto-temporale gauche (Hamberger & Cole, 2011). La spécialisation et l'intégration interhémisphérique ont ainsi la possibilité d'être modulées pour compenser un dommage cérébral dans un hémisphère spécifique si les conditions sont optimales à une réorganisation cérébrale. Somme toute, bien que la littérature scientifique actuelle soit très informative quant à la distribution des fonctions cognitives entre les deux hémisphères cérébraux, davantage d'études sont nécessaires pour mieux comprendre l'intégration interhémisphérique et la dynamique entre la spécialisation et l'intégration.

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