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Investigation of the Development of Neural and Behavioural Auditory Rhythmic Sensitivity and of its Contribution to Reading Acquisition

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Acknowledgment

I seriously believe in the *emergence* of this work. Importantly, the word *believe* is used here with its most *supernatural* sense, a sense that will no doubt contrast with the scientific standards followed closely across the implementation of the experiments that the reader will encounter throughout this work. I *believe* that this work is the product of the multiple sums and multiplications (and divisions and subtractions, when needed) of the thoughts and emotions that my family, friends and colleagues have fed me with throughout my life. The intention of this rather eccentric way of starting the acknowledgement section is to highlight the fact that this cannot be considered a work of which I am the sole author. Instead, I *believe* it is *written* by the many that have surrounded me during the last four years, and by the ones who have been there since I remember. I will try to thank these various groups of individuals separately to come closer to a conventional acknowledgement; although the reader should keep in mind that I do not think that I can separate these several contributions either among them, or from my own.

It goes without saying that the undiscussed protagonists of this story are the forty-two children that enrolled for this study when it was only a proposal in paper. To their parents, and their uninterested help, my biggest gratitude.

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Resumen

El habla es una señal compleja que puede dividirse en componentes de frecuencia que proporcionan información a distintas escalas temporales. Las variaciones en amplitud (en presión) de la señal lingüística a estas escalas generan los característicos ritmos del habla. Los ritmos más prominentes se corresponden con la aparición cuasi-periódica de las unidades fundamentales del lenguaje: los fonemas, las sílabas y las marcas prosódicas. A su vez, la actividad cerebral es también una onda compleja cuyos componentes de frecuencia pueden examinarse por separado. Este análisis muestra que la señal cerebral está caracterizada por la presencia de variaciones rítmicas en amplitud (oscilaciones) a distintas frecuencias. Estas oscilaciones están presentes en el cerebro de manera espontánea (sin estimulación), pero también se *acoplan* (o sincronizan) a los estímulos externos.

Gracias a la posibilidad de dividir tanto la señal lingüística como la cerebral en sus componentes de frecuencia, es posible realizar análisis de tiempo-frecuencia para investigar el comportamiento de las distintas oscilaciones cerebrales en respuesta a los distintos ritmos del habla. A este respecto, se ha demostrado que la actividad cerebral a distintas frecuencias se sincroniza con los distintos ritmos del habla. Concretamente, durante la exposición al habla, las oscilaciones a frecuencias delta (<4 Hz) y theta (4-8 Hz) se sincronizan con los cambios en amplitud generados por las marcas prosódicas y la sucesión de sílabas, respectivamente. A su vez, las oscilaciones de la banda gamma (>30 Hz) samplean con fidelidad la información espectral a nivel del fonema. Este hecho ha propiciado la aparición de teorías que asignan a la sincronización cerebral un papel fundamental en los procesos de percepción del habla. Entre estas teorías, los modelos de resolución *multi-temporal* del habla (ej. Poeppel, 2003) proponen que los hemisferios cerebrales están especializados en codificar la información a distintas escalas temporales. Así, el hemisferio derecho estaría especializado en codificar la información a frecuencias bajas (<8 Hz), encargándose por tanto de procesar la información prosódica y silábica, mientras que la información a frecuencias altas, esto es la información espectral fina o fonémica, se procesaría preferentemente en el hemisferio izquierdo o bilateralmente. Una vez codificada el habla en función de sus componentes de frecuencia, el cerebro debe estar dotado de un mecanismo para integrar toda la información y generar un único acto de habla, que es lo que

en realidad percibimos. Los modelos de resolución *multi-temporal* del habla proponen que esta integración se lleva a cabo gracias a la naturaleza jerárquica de las oscilaciones cerebrales. De hecho, las distintas ondas cerebrales no se comportan de manera anárquica en el cerebro, sino que la actividad de las frecuencias más altas está modulada por la de las frecuencias más bajas (p. ej., las ondas theta modularían la actividad de las ondas gamma) en un proceso denominado acoplamiento entre-frecuencias (*cross-frequency coupling*). De esta forma, la información a frecuencias altas podría integrarse con la información a frecuencias bajas. Estos modelos han recibido abundante apoyo neurofisiológico y se ha demostrado que la sincronización cerebral al habla está relacionada con procesos fundamentales para la percepción del habla.

Una adecuada percepción del habla es esencial, por ejemplo, para la adquisición de la conciencia fonológica, esto es del conocimiento explícito de que el lenguaje está formado por sonidos individuales o fonemas y por su combinación. La conciencia fonológica es a su vez una habilidad cognitiva íntimamente ligada a la adquisición de la lectura, dado que la *calidad* de las representaciones de los sonidos del habla jugará un papel fundamental en los procesos de aprendizaje de las correspondencias arbitrarias entre los sonidos (fonemas) y su representación escrita (grafemas). En vista de la relación entre percepción del habla y conciencia fonológica, se ha dedicado un considerable esfuerzo investigador para desentrañar qué aspectos de la percepción del habla son esenciales para la adquisición de una conciencia fonológica apropiada. En esta línea, múltiples estudios han desvelado que, junto con el déficit fonológico, muchos de los individuos que sufren trastornos evolutivos de la lectura (dislexia evolutiva) también muestran un déficit en la percepción de los ritmos lentos del habla. Dado que la percepción de estos ritmos está relacionada con la sincronización cerebral a frecuencias bajas, se ha propuesto que el déficit primario de los individuos disléxicos radicaría en una alineación temporal atípica de las oscilaciones cerebrales del hemisferio derecho con la sucesión de sílabas y marcas prosódicas en la señal lingüística. A su vez, dada la naturaleza jerárquica de las oscilaciones cerebrales, este déficit en la sincronización con los ritmos lentos en el hemisferio derecho daría lugar al procesamiento atípico de la información espectral que ocurre a frecuencias altas en el hemisferio izquierdo o bilateralmente, lo que afectaría a la calidad de las representaciones fonémicas/fonológicas y derivaría por consiguiente en problemas de adquisición de la lectura. Estas teorías han recibido un apoyo sustancial a nivel tanto neurofisiológico como conductual.

Por un lado, los individuos con dislexia evolutiva muestran una sincronización cerebral atípica en las bandas de frecuencia delta y theta tanto en respuesta al habla natural como en respuesta a señales acústicas cuya amplitud se ha modulado artificialmente para emular los ritmos lingüísticos a nivel silábico y prosódico. Por otro lado, también muestran un déficit conductual de sensibilidad al ritmo que se manifiesta en tareas tanto de recepción como de producción rítmica. No obstante, a pesar de este apoyo experimental, casi la totalidad de la evidencia que relaciona sincronización cerebral y lectura proviene de estudios transversales, por lo que no es posible establecer una relación causal entre ambas. Por otra parte, prácticamente todos los estudios realizados hasta ahora han estudiado la relación entre sincronización cerebral y lectura en individuos disléxicos. Sin embargo, si la contribución de esta sincronización es fundamental para la adquisición de la lectura como proceso cognitivo general, la relación entre sincronización al ritmo y lectura también debería estar presente en los individuos normolectores. Por último, a pesar de que los individuos disléxicos muestran déficits tanto en sincronización neural como en sincronización conductual, escasos estudios han examinado ambas conjuntamente para probar experimentalmente que están relacionadas y, en caso negativo, comparar cuál es su contribución individual al desarrollo de la lectura.

El objetivo principal de esta tesis doctoral fue el de investigar la trayectoria evolutiva de la sincronización neural con los componentes lentos del habla durante la infancia y su contribución al desarrollo típico de la lectura. Además, otro de sus objetivos era el de comparar el potencial de la sincronización rítmica a nivel neural y conductual para predecir el desarrollo lector. Con tales fines, se realizó un experimento longitudinal en el que una cohorte de niños fue examinada en tres momentos: tras finalizar el penúltimo curso de la escuela infantil (Fase 1; edades entre cuatro y cinco años), tras finalizar el último curso de la escuela infantil (Fase 2; edades entre cinco y seis años) y tras finalizar el primer curso de la escuela primaria (Fase 3; edades entre seis y siete años). En el País Vasco la instrucción formal de la lectura se introduce comúnmente en el primer año de educación primaria, por lo que los niños recibieron instrucción formal en lectura en el intervalo que separaba las Fases 2 y 3 de este estudio. Tal instrucción se llevó a cabo en euskera. Se utilizó la técnica de electroencefalografía (EEG) para evaluar la sincronización neural de los niños en respuesta al lenguaje natural y en respuesta a señales cuya amplitud se moduló artificialmente siguiendo intervalos prosódicos (2 Hz), silábicos (4 Hz) y fonémicos (30 Hz). La sincronización cerebral se evaluó con una medida de coherencia en fase que permite examinar la alineación entre la fase de la señal acústica y la cerebral. Los niños también completaron una batería que incluía las tareas utilizadas de manera habitual para evaluar los predictores de la lectura (conocimiento de letras del alfabeto, *RAN*, memoria fonológica a corto plazo, memoria de trabajo y conciencia fonológica) y una tarea conductual de sincronización activa al ritmo. En esta última, los niños tenían que golpear un tambor electrónico siguiendo un ritmo externo a 1.67 Hz (banda delta). Se utilizó estadística circular para analizar la consistencia en fase entre el ritmo externo y el ritmo producido por los participantes. En la última fase del estudio (Fase 3), también se evaluaron sus habilidades lectoras.

Los resultados revelaron interesantes trayectorias evolutivas de sincronización cerebral en respuesta al habla en la banda de frecuencia delta (0.5 Hz; Experimento 1) y en respuesta a señales moduladas a intervalos prosódicos (2 Hz) y silábicos (4 Hz; Experimento 2). En contraste, no se encontró coherencia significativa del cerebro a ninguna frecuencia alta ni en el experimento con el lenguaje natural, ni en el experimento con las señales moduladas. En conjunto, esta evidencia demostró que la sincronización a los ritmos lentos del lenguaje podría jugar un papel fundamental en los procesos de percepción del habla, de acuerdo con lo propuesto por los modelos de resolución *multi-temporal* del lenguaje. El desarrollo diferencial de la actividad cerebral sincronizada a diferentes bandas de frecuencia se discutió en el seno de estos modelos.

El presente estudio reveló por primera vez en la literatura que la coherencia en fase a 0.5 Hz en el hemisferio derecho en respuesta al lenguaje natural en estadios pre-lectores (Fase 2) predecía significativamente el rendimiento lector futuro (Fase 3; Experimento 3), proporcionando por tanto evidencia sobre la relación posiblemente causal entre sincronización cerebral y desarrollo de la lectura propuesta por modelos recientes sobre dislexia evolutiva. Además, los niños que mostraban un incremento mayor en coherencia entre las Fases 2 y 3 del estudio (cuando los niños recibieron instrucción formal en lectura) mostraban peor rendimiento lector en la Fase 3. Basado en estudios anteriores, se concluyó que tal incremento podría reflejar un mecanismo compensatorio. Por el contrario, no se encontró ninguna relación significativa entre lectura y sincronización cerebral en respuesta a las señales moduladas a intervalos prosódicos o silábicos. Aunque la ausencia de esta relación podría deberse a aspectos de poder estadístico, el hecho de que se encontrara una relación entre sincronización cerebral con el habla y no con las señales moduladas sugiere que la sincronización con la señal lingüística natural, una señal con una estructura temporal mucho más rica y dotada de información fonológica, podría ser un estímulo más adecuado a la hora de capturar las sutiles diferencias entre-individuos que caracterizan a los grupos normolectores.

En cuanto a la tarea de sincronización rítmica conductual, se encontró que el rendimiento en ésta estaba íntimamente relacionado con los predictores de la lectura antes de que la lectura se introdujera formalmente en el currículo escolar (Experimento 4). Concretamente, el rendimiento en la tarea rítmica en las Fases 1 y 2 estaba correlacionado positivamente con el rendimiento, por ejemplo, en las tareas de memoria fonológica a corto plazo y conocimiento de las letras del alfabeto. Sin embargo, esta relación se debilitó en la última fase del estudio, de manera que la sincronización conductual en la Fase 3 no estaba relacionada con ningún predictor de la lectura. Además, la lectura no estaba significativamente relacionada con el rendimiento en la tarea rítmica en ninguna de las fases. Estos resultados sugirieron que la relación entre ritmo conductual y lectura, al menos con las medidas utilizadas en este estudio, podría estar limitada a estadios muy tempranos del desarrollo de la lectura y que su papel podría disminuir a medida que aumenta la competencia lectora.

Por último, se compararon directamente las medidas de sincronización neural y la medida de sincronización conductual (Experimento 5). Este análisis reveló que las correlaciones entre estas medidas eran inestables o incluso negativas, lo que sugirió que la relación entre sincronización neural y conductual podría ser más indirecta de lo que se había sugerido anteriormente, o visible exclusivamente en condiciones concretas de estimulación y análisis.

En conjunto, los resultados sugirieron que la sincronización neural del hemisferio derecho a 0.5 Hz en respuesta al habla antes de la enseñanza de la lectura podría ser un marcador electrofisiológico del rendimiento lector futuro. Por su parte, la sincronización conductual en estados pre-lectores podría ser un buen índice de predisposición lectora, pero su relación con la lectura podría ser más indirecta, cuestión que deberá ser abordada por futuros estudios.

Abstract

The phonological deficit that characterises developmental reading disorders has been consistently associated with atypical sensitivity to the rhythms originated by the quasi-periodic succession of syllables and prosodic stress in the speech stream. The *temporal sampling* framework was originally proposed by Goswami (2011) as an integrative account that provides a neurological basis for the existence of both rhythmic and phonological deficits in dyslexia. This theory proposes that the core deficit of dyslexia would lie on atypical temporal alignment of brain oscillations at low-frequency bands with the pace of syllables and prosodic stress in the linguistic signal. Such deficit would lead to hampered processing of fast-occurring spectral information, which would in turn affect the quality of phonemic/phonological representations and lead to reading disorders. Although the theory has received substantial neurophysiological and behavioural support in the field of dyslexia, if neural entrainment to the low frequencies of speech is *necessary* for the development of reading, this relation should also be present during the acquisition of typical reading. Nevertheless, no study until now was able to provide support for the causal contribution of brain oscillatory activity at low-frequency bands for future reading development.

The main aim of this doctoral work was to fill this gap in the literature examining the developmental trajectory of neural entrainment to linguistic and non-linguistic auditory sequences and its contribution to reading development. Moreover, we also wanted to examine the possibility that neural entrainment at low-frequency bands was reflected in behavioural rhythmic entrainment and that their potential to predict reading abilities was therefore comparable.

We tested a cohort of children prior to (T1 and T2) and after (T3) receiving formal reading instruction. We used EEG to evaluate children’s brain oscillatory activity in response to natural speech and non-linguistic acoustic signals modulated at the prosodic (2 Hz), syllabic (4 Hz) and phonemic (30 Hz) rates. Children also completed a battery of tasks measuring classical reading predictors (letter name knowledge, RAN, phonological-short term memory, working

memory and phonological awareness) and a tapping to a beat task at delta rates (1.67 Hz) to examine their behavioural rhythmic entrainment. At T3, children's reading skills were evaluated.

Our results revealed interesting developmental trajectories of phase-coherent low-frequency responses to speech (0.5 Hz; Experiment 1) and to amplitude modulated (AM) signals at the prosodic (2 Hz) and syllabic (4 Hz) rates (Experiment 2) during childhood. By contrast, we did not find coherent activity at high-frequency bands either for the speech or for the 30-Hz AM signals at any testing time. This differential development of activity in the different frequency bands is discussed in relation to current neurobiological models of speech perception.

Importantly, we showed that pre-reading right-hemisphere coherence to speech within the delta range (0.5 Hz) was able to predict reading performance after literacy instruction (Experiment 3). Although the result was statistically weaker, we also found a relation between the longitudinal change in coherence along this period (from T2 to T3) and reading acquisition, such that children with larger increase in right-hemispheric coherence performed worse in the reading tasks in T3. This evidence suggests that prior-to-instruction right-hemispheric coherence in response to speech could be an electrophysiological marker of future reading achievement, and that a larger (probably compensatory) increase in coherence during initial formal reading instruction would be related to poorer (although non-pathological) reading skills. By contrast, coherence to non-linguistic amplitude-modulated signals was not correlated with reading achievement, suggesting that the neural entrainment-rhythm relation might be mediated by the verbal component and/or the (less periodic) temporal structure of natural speech.

Finally, we found that behavioural rhythmic entrainment was tightly related to other reading predictors in pre-reading stages (T1 and T2), but did not predict reading itself at T3, suggesting that the rhythm-(typical) reading relation might change as the children acquire reading experience, such that purely perceptual indexes might lose weight once children are past very initial reading stages (Experiment 4). Our last experiment comparing behavioural and neural rhythmic entrainment at the delta band (Experiment 5) suggested that, at least with the analyses and stimulation rates we used, these measures might not be as comparable as previously suggested, and that such relation must be further explored.

Table of contents

Abbreviations and acronyms

AC	auditory cortex
ADHD	attention deficit hyperactivity disorder
AE	amplitude envelope
AIC	Akaike information criterion
AM	amplitude modulation / amplitude-modulated
ANCOVA	analysis of covariance
ANOVA	analysis of variance
AoA	age of acquisition
ASHA	American Speech-Language-Hearing Association
ASSR	auditory steady-state response
AST	asymmetric sampling in time
AV	audiovisual
BCBL	Basque Center on Cognition, Brain and Language
BEST	Basque, English and Spanish Test
BS	Basque
BSynch	beat synchronization
CA	controls matched in age
cABR	complex auditory brainstem response
CCV	consonant-vowel-vowel
CI	change index
CL	confidence level
Coh	coherence
CRT	cathode ray tube
CV	consonant-vowel
dB	decibel
DD	developmental dyslexia
dom	(language) dominance
DSB	digit span backward
EEG	electroencephalography

EOG	electrooculography
ERF	event-related field
ERP	event-related potential
FDR	false discovery rate
fMRI	functional magnetic resonance imaging
freq	frequency
GR	good readers
hem	hemisphere
HSD	honestly significant difference
Hz	hertz
ICA	independent component analysis
IQ	intelligence quotient
ISI	inter-stimulus interval
ITC	inter-trial coherence
lat	lateralization
LI	lateralization index
LIFG	left inferior frontal gyrus
LNK	letter name knowledge
LSM	least square mean
MEG	magnetoencephalography
ML	maximum likelihood
MRI	magnetic resonance imaging
NIRS	near-infrared spectroscopy
non-synch	non-synchroniser
n-p	non-parametric
PET	positron emission tomography
PhDel	phoneme deletion/elision
PLV	phase locking value
PR	poor readers
PSTM	phonological short-term memory
PWRep	pseudoword repetition

Q+I	questionnaire + interview
RA	controls matched in reading level
RAC	right auditory cortex
RAN	rapid automatized naming
REML	restricted maximum likelihood
SES	socioeconomic status
SP	Spanish
SPL	sound pressure level
SS-EP	steady-state evoked potential
subj	subject
synch	synchroniser
T1	testing time 1
T2	testing time 2
T3	testing time 3
TD	typically developing
TS	temporal sampling
TT	testing time
WISC	Wechsler Intelligence Scale for Children
WPPSI	Wechsler Preschool and Primary Scale of Intelligence

Chapter 1: Theoretical background

This first chapter presents the theoretical background upon which this doctoral dissertation was conceived. An introductory section on the different rhythms that characterise the linguistic signal (section 1.1) is followed by the presentation of neurophysiological theories that propose neural oscillations as a mechanism to explain their integration for the successful perception of speech (section 1.2). The chapter concludes presenting an over-arching theory that proposes brain oscillatory mechanisms to play a causal role in reading development (section 1.3).

1.1. The rhythms of the speech signal

The analysis of the physical properties of the speech signal reveals that within it, two clear components can be distinguished (Figure 1.1): i) the fine structure component, defined as the fast pressure variations that provide information on its spectral content; and ii) the envelope component, which results from the amplitude modulations (AMs) of the speech's fine temporal structure. These energy (pressure) variations of the acoustic signal over time give rise to the speech amplitude envelope (AE; Rosen, 1992).

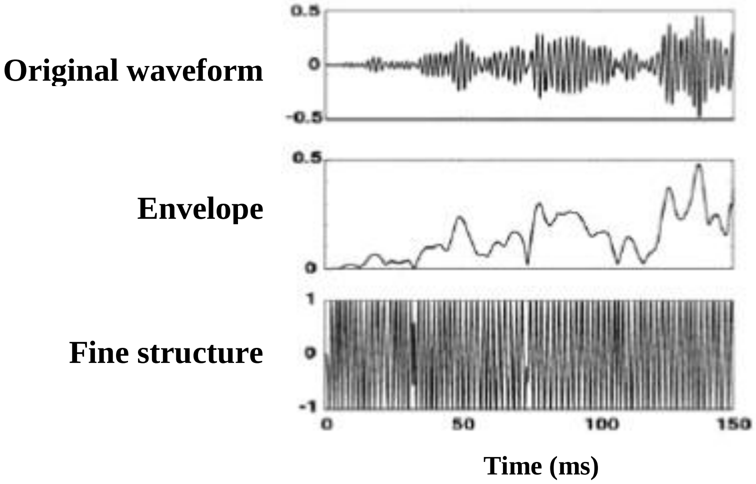

Figure 1.1. Decomposition of complex speech signal in fine structure and amplitude envelope

Detailed analysis of the temporal structure of the AE further reveals that its fluctuations in amplitude occur at different pseudo-periodic rates that mark the succession of phonemes, syllables and prosodic stress (or phrasal boundaries) in the linguistic signal. Importantly, although all the information contained in the amplitude envelope contributes significantly to the intelligibility of the speech signal (Drullman, Festen, & Plomp, 1994; Horst, Leeuw, & Dreschler, 1999; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995), most of the information on the speech structural rhythm is contained in the low frequencies of the AE (<8 Hz; Houtgast & Steeneken, 1985), namely in the amplitude fluctuations that mark the succession of syllables (syllabic amplitude modulations or AMs) and prosodic stress (prosodic AMs; Figure 1.2.).

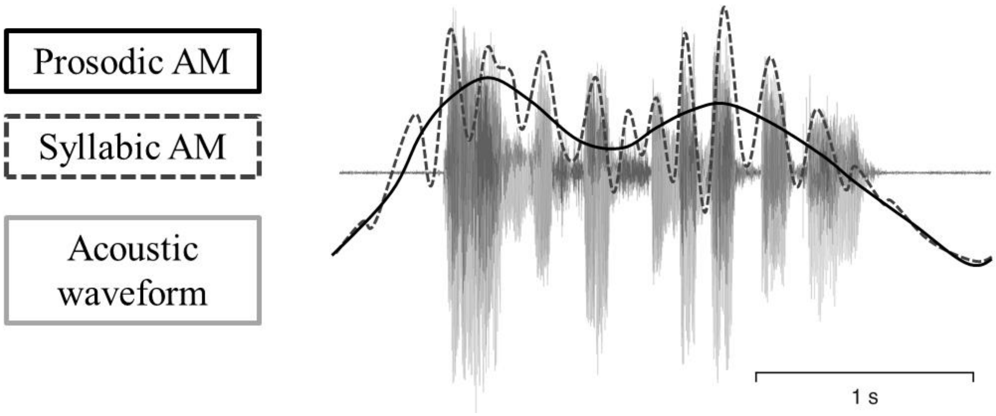

Figure 1.2. Time (x-axis)-amplitude (y-axis) representation of a speech waveform (light grey) with superimposed band-pass filtered envelop representing syllabic AM (theta band; 4-8 Hz; dotted grey line) and prosodic AM (delta band; <1 Hz; black plain line). Adapted from Lallier et al. (2018)

In view of the complex temporal nature of the linguistic signal, we are confronted with a question that may well be defined as the *temporal binding question* of speech: if the final speech signal emerges from the combination of information at the phonemic, syllabic and prosodic temporal scales, how does the brain integrate such temporally disparate information so that we finally perceive the speech signal as a unified percept? Multi-temporal resolution models of speech have made use of the potential of neural oscillations to answer this question.

1.2. Multi-temporal resolution models of speech

The joint excitation and inhibition of populations of neurons produces large-scale fluctuations of neural activity or *neural oscillations* that are visible in any (non-pathological) electrophysiological recording of the human brain (Buzsáki, 2006). Neural oscillations occur spontaneously (in the absence of related stimulation), but can also be evoked (phase-locked or *entrained* to external stimuli). The *neural entrainment* phenomenon, i.e. the ability of the brain to synchronise its rhythms to an external stimulus, has fed an active view of brain oscillators as mechanisms through which neural populations across the brain would communicate to support complex cognitive operations, from inhibition (e.g. Klimesch, Sauseng, & Hanslmayr, 2007), to visual temporal attention (e.g. Mathewson et al., 2012) or selective attention (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008).

Given that, as explained in section 1.1, language is a complex auditory objet that contains (pseudo-)rhythmic modulations at different frequencies, neural entrainment occurs also with auditory linguistic input (Figure 1.3). Moreover, interestingly enough, the rate of the most predominant brain oscillations at rest coincides with the rate of appearance of the salient linguistic units, such that phonemes occur at rates within the gamma range (at ~80 ms), syllables within the theta range (at ~200 ms) and prosodic stress (or stress marking phrasal boundaries) within the delta range (at ~500 ms; Ghitza & Greenberg, 2009; Goswami, 2011). Using acoustic signals amplitude-modulated at different frequency rates, several studies have reported that the auditory system is able to track the AMs of the acoustic signal (i.e. its envelope) at multiple levels with surprising precision (Bendor & Wang, 2007; Brugge et al., 2009; Middlebrooks, 2008; Nourski et al., 2009).

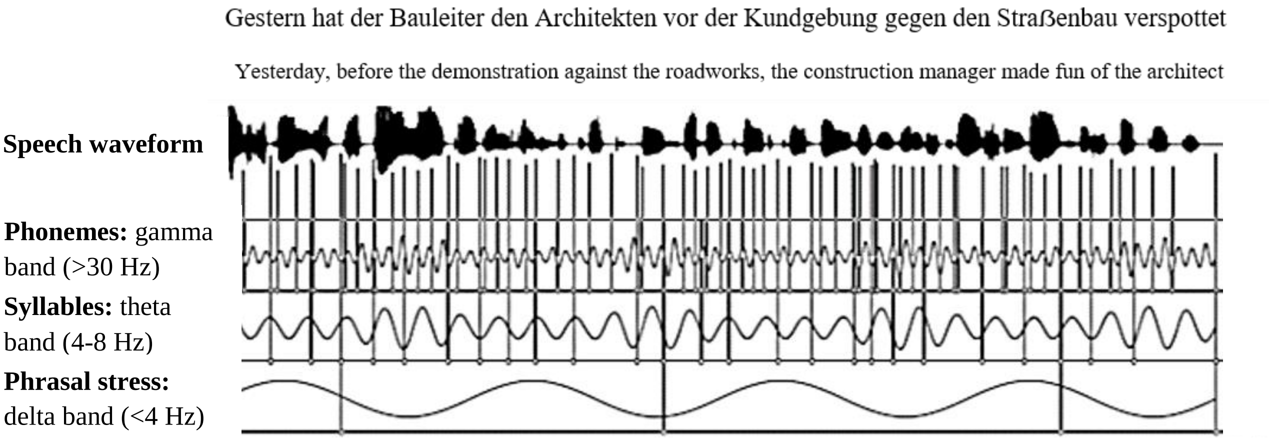

Figure 1.3. Neural oscillations during speech processing. Cerebral oscillations synchronise to the speech signal in the gamma (phoneme level), the theta (syllable level) and the delta (phrasal stress level) bands. Adapted from Meyer, 2017.

The fundamental functional role that neural oscillations might play for language processing has been shown in multiple studies that have related positively the magnitude of entrainment with intelligibility/comprehension ratings (Gross et al., 2013; Howard & Poeppel, 2010; Keitel, Gross, & Kayser, 2018; Luo & Poeppel, 2007; Nourski et al., 2009; Park, Ince, Schyns, Thut, & Gross, 2015; Peelle, Gross, & Davis, 2013) or with the ability to perceive speech in noise (Ding & Simon, 2012a; Vander Ghinst et al., 2016; Zion Golumbic et al., 2013).

Neural entrainment has been proposed to occur thanks to the phase alignment of the (previously random) phase of ongoing oscillations to the external speech stimulus (Peelle & Davis, 2012). Indeed, it has been shown that rapid AMs of the speech signal reset the phase of neural oscillations in the gamma, theta and delta bands (Gross et al., 2013). Such a phase reset would allow neural populations to adapt their neural excitability to be aligned with the temporal structure of speech and hence facilitate spectral analysis (Figure 1.4; Peelle & Davis, 2012).

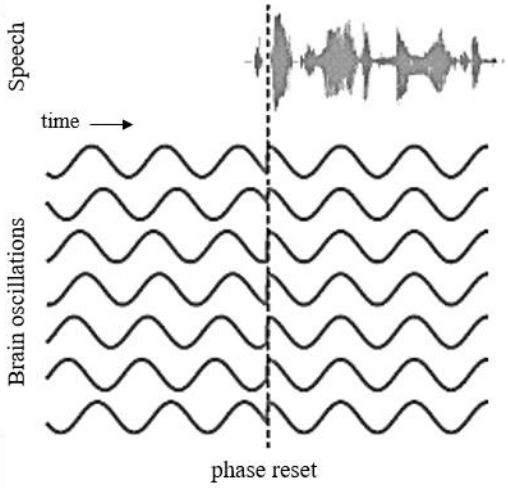

Figure 1.4. Illustration of how an external stimulus can reset the ongoing phase of neural oscillations. The oscillations' phases align to the stimulus, while they were random prior to this. Adapted from Peelle & Davis (2012).

The dynamic nature of brain oscillatory mechanisms in response to speech suggests that neural oscillations could support the operations necessary to integrate different speech rhythms, i.e. to resolve the speech *temporal binding* problem. Actually, this is the main claim of recent neurophysiological multi-temporal resolution models such as the *asymmetric sampling in time* or AST hypothesis (Boemio, Fromm, Braun, & Poeppel, 2005; Poeppel, 2003; Poeppel, Idsardi, & Van Wassenhove, 2008). Specifically, according to the AST, the specialization of neural oscillations would also be coded in cerebral asymmetries, such that the brain hemispheres would collaborate in the resolution of the time conundrum presented by the speech signal. In this line, they propose that whereas neurons in the right auditory cortex would preferably synchronise to AMs at low frequencies (long temporal integration window; 150-250 ms; theta band), the left hemisphere would show a preference for processing AMs at high frequencies (short temporal integration window; ~20-40 ms; gamma band). Here it is important to note that, although the delta band was somehow underrepresented in the original AST proposal, its relevance for speech processing has been fairly proven by multiple studies evaluating cerebral oscillations in response to speech (Bourguignon et al., 2013; Ding & Simon, 2014; Gross et al., 2013; Keitel et al., 2018; Molinaro, Lizarazu, Lallier, Bourguignon, & Carreiras, 2016; Molinaro & Lizarazu, 2018). Supporting the multi-time resolution hypothesis, delta and theta oscillations in response to the prosodic and syllabic modulations of speech and to AMs at low-frequencies (<8 Hz) are predominantly coded in the right hemisphere (Abrams, Nicol, Zecker, & Kraus, 2008; Bourguignon et al., 2013; Doelling, Arnal, Ghitza, & Poeppel, 2014; J. A. Hämäläinen, Rupp, Soltész, Szücs, & Goswami, 2012; Lizarazu et al., 2015), while phonemic variations and AMs at high-frequency rates are closely tracked by gamma power activity in the left hemisphere or bilaterally (Boemio et al., 2005; Di Liberto, O'Sullivan, & Lalor, 2015; Gross et al., 2013; Lehongre, Ramus, Villiermet, Schwartz, & Giraud, 2011). Importantly, hemispheric specialization at the functional level is supported by inter-hemispheric differences in brain anatomy, both at the macroscopic and the microscopic level. On the one hand, at the macroscopic level cerebral hemisphere asymmetries (normally in favour of the left hemisphere) are consistently found for areas well documented to be involved in language processing such as the *planum temporale* (Geschwind & Levitsky, 1968; Geschwind & Galaburda, 1985). On the other hand, microanatomical specializations of neurons in the left and the right hemispheres have been consistently linked to the implementation of cognitive functions (see Hutsler & Galuske, 2003 for a review). Whereas long term integrating neurons are larger in proportion in the right hemisphere, and hence would be better equipped to parse low-frequency modulations, short-term integrating neurons would be more present in the left hemisphere and would in turn specialise in tracking high-frequency modulations (Poeppel et al., 2008). Specifically, the right-hemispheric bias for processing the slow components of speech has been suggested to be innate, since it has been found in studies with infants and young children (De Vos, Vanvooren, Vanderauwera, Ghesquière, & Wouters, 2017; Telkemeyer et al., 2011). Nevertheless, it is important to note that these studies used *amplitude* measures, while studies in adults exploring low-frequency entrainment have typically found the right-hemispheric bias in terms of *phase* (see section 2.2.3 in Chapter 2 for a distinction between amplitude and phase measures). In any case, the functional role of hemispheric asymmetries for language processing is a matter of ample debate (McGettigan & Scott, 2012), with other theoretical lines suggesting that specialization relies on the linguistic *versus* non-linguistic nature of the stimulus (Rosen, Wise, Chadha, Conway, & Scott, 2011), or on the processing of the temporal *versus* spectral components of the signal (Zatorre & Belin, 2001).

The evidence reviewed up to now speaks in favour of the hypothesis that, when confronted with a temporally complex auditory signal like speech, different populations of neurons, grouped as a function of their location in the cortex, would collaborate to *de-multiplex* (decompose) the speech signal in its multiple frequency components, allowing hence parallel processing of components at different temporal scales. A crucial step is though missing here, since *de-multiplexing* the speech signal would not be of much use if it were not followed by the integration of the different temporal components which will at last allow the unitary perception of speech (our *binding* problem). This has been described as the *encoding* step (Gross et al., 2013; Lizarazu et al., 2015), for which cross-frequency coupling mechanisms (i.e. coupled activity between different frequency bands) have been previously described. Oscillations do not operate independently in the brain, but under a hierarchical order according to which the activity of high-frequency bands would be modulated by the activity of lower frequencies (Canolty et al., 2006; Gross et al., 2013; Lakatos et al., 2005; Lisman & Jensen, 2013). For language processing, this orchestrated behaviour of neural oscillations is normally reflected in terms of phase-amplitude coupling (i.e. the amplitude of the higher frequency couples to the phase of the lower frequency) and is supported by an increasing number of studies (Giraud & Poeppel, 2012; Gross et al., 2013; Kayser, Wilson, Safaai, Sakata, & Panzeri, 2015). In this line, both gamma-theta (Morillon, Liégeois-Chauvel, Arnal, Bénar, & Giraud, 2012), and theta-delta (Gross et al., 2013; Lakatos et al., 2005) amplitude-phase couplings have been described by previous experiments. According to multi-temporal resolution models, the integration of information across the different temporal scales would take place through this coupling mechanism, which would allow the brain to align its neural responses (neural excitability) with spectral information in the speech stream occurring at fast rates and hence facilitate processing at the phonemic level (Giraud et al., 2007; Giraud & Poeppel, 2012). From this it follows that the *quality* of fine-grained spectral (phonemic) processing should in principle depend on the *quality* of entrainment to the slow (syllabic and stress) temporal components of speech. If that is the case, the consequences of sub-optimal low-frequency entrainment could evidently affect speech perception (e.g. intelligibility), and experiments in lab-settings have shown so (e.g. Ahissar et al., 2001; Doelling et al., 2014; Peelle & Davis, 2012). Interestingly, atypical neural entrainment to the low-frequency components of speech and to amplitude modulations (AMs) at slow rates has also been consistently found in dyslexic children and adults (Di Liberto et al., 2018; J. A. Hämäläinen et al., 2012; Lallier, Molinaro, Lizarazu, Bourguignon, & Carreiras, 2017; Lizarazu et al., 2015; Molinaro et al., 2016; Power, Colling, Mead, Barnes, & Goswami, 2016; Power, Mead, Barnes, & Goswami, 2013), suggesting that this line of study could shed light into the long-debated origins of developmental reading disorders.

1.3. An oscillatory temporal-sampling theory for reading development

The complexity of the cognitive processes involved in reading acquisition is reflected in the fact that from 3 to 10% of children that receive proper formal literacy instruction fail to acquire it appropriately in the absence of other severe cognitive impairments, i.e. suffer from developmental reading disorders (Bishop & Snowling, 2004; Snowling, 2001). Given the importance of learning to read for the adequate integration of Western individuals in the academic and work environments, the study of such complexity has been devoted a great amount of research during the last decades. Acknowledging its complex nature, an increasing number of researchers agree on the fact that dyslexia cannot be attributed a single cause, and multi-factorial accounts of the disorder proliferate in the literature (e.g. Menghini et al., 2010; Peyrin et al., 2012). Nevertheless, the fact is that dyslexic individuals show persistent deficits in phonological processing (Landerl et al., 2013) and that such deficits are mainly characterised by an inadequate phonological awareness, defined as the explicit awareness that speech is constituted by individual sounds (phonemes) and their combinations (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Logically, difficulties in the identification, manipulation or access to sounds would lead to the hampered acquisition of the (arbitrary) mapping between phonemes and graphemes, and eventually to reading disorders (Ramus, 2003).

Transversal studies stating the differences in phonological processing between individuals who have already acquired reading (more or less successfully) can only inform on the presence of a deficit, whereas the sole way to actually understand (and remediate) it is to explore its origins, i.e. to explore what is/are the cause/s of the inter-individual differences in phonological processing. In this line, there is abundant evidence that the quality of the child's speech perception experience from birth plays a core role for the acquisition of proper phonological skills (e.g. Leppänen et al., 2012; Lyytinen et al., 2001). But what aspects of the linguistic signal are crucial for anchoring speech perception, and in turn for the formation of appropriate phonological skills and reading? Accumulating evidence points to the perception (or the sensitivity to) the slow speech rhythms as a golden candidate to answer to this question (see Wood, Wade-Woolley, & Holliman, 2009 for a review). Indeed, infants have been shown to use the slow speech rhythms to differentiate among languages (Mehler et al., 1988), to discriminate sequences of strong and weak syllables (Jusczyk & Thompson, 1978) or, importantly, to segment the speech signal into its constituents (Ramus, Hauser, Miller, Morris, & Mehler, 2000).

The core role that rhythm sensitivity plays for speech processing during infanthood and childhood has boosted the appearance of theories suggesting that appropriate perception of the slow rhythms of speech might be essential for the acquisition of adequate phonological representations, and in turn of reading (Goswami, 2011; Goswami, Power, Lallier, & Facoetti, 2014; Lallier et al., 2018, 2017). Supporting the idea that the perception of speech rhythms is related to the acquisition of phonological skills, abundant evidence has found that dyslexic individuals show abnormal perception of the slow amplitude changes in the linguistic signal that code for the stress and the syllabic rhythms, and that such deficits are correlated with their phonological processing skills (Corriveau, Goswami, & Thomson, 2010; Huss, Verney, Fosker, Mead, & Goswami, 2011; Richardson, Thomson, Scott, & Goswami, 2004; Thomson, Fryer, Maltby, & Goswami, 2006). In particular, it has been found that dyslexics struggle to perceive rises in amplitude that code for the onset of syllables, what is known as *amplitude rise times* (Goswami & Leong, 2013; Goswami et al., 2002; J. A. Hämäläinen et al., 2009; Leong, Hämäläinen, Soltész, & Goswami, 2011; Richardson et al., 2004). Similarly, dyslexic individuals also perform worse in rhythm production tasks, suggesting that the rhythm disorder in dyslexia affects sensori-motor integration (Colling, Noble, & Goswami, 2017; Corriveau & Goswami, 2009; Flaugnacco et al., 2014; Thomson & Goswami, 2008).

In the endeavour to find the underlying causes of the rhythmic perception difficulties in dyslexics, scientists have turn to the study of the brain in search of a mechanism that would explain both the phonological and the rhythm-related deficits in dyslexia. In this line, it has been shown that dyslexic individuals show abnormal brain oscillatory (rhythmic) responses to the envelope of natural speech at the delta and the theta bands (Abrams, Nicol, Zecker, & Kraus, 2009; Molinaro et al., 2016; Power et al., 2016), to the envelope of syllables presented periodically (Power et al., 2013) and to the envelope of non-linguistic acoustic signals amplitude modulated (AM) at rates relevant for speech perception at the phoneme, syllabic and prosodic level (De Vos et al., 2017; J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Poelmans, Luts, Vandermosten, Ghesquière, & Wouters, 2012).

In view of the fact that the phonological deficit of dyslexic individuals is usually accompanied by a deficit in rhythmic processing, and that this deficit is also visible in the brain, Goswami (2011, 2018; Goswami et al., 2014) proposes an oscillatory *temporal sampling* (TS) framework that strives to integrate all this evidence (and beyond) in a comprehensive neurobiological theory that makes use of the dynamics of brain oscillatory activity reviewed in section 1.2. According to the TS, the phonological deficit of dyslexia would have its origin in atypical right-hemisphere entrainment to the low-frequency components of speech, and particularly in encoding the phase relation between rise times (i.e. the temporal succession of rises in amplitude), which is essential to perceive lexical stress (Goswami & Leong, 2013). Making use of the hierarchic nature of neural oscillations, the TS proposes that a deficit in encoding amplitude changes at slow temporal rates would hamper the accurate perception of (fast) spectral phonemic information, and lead to the formation of inappropriate phonemic representations and in turn to reading disorders (Giraud & Poeppel, 2012; Goswami, 2011). Due to the specialization of the cerebral hemispheres in different temporal scales, it has been proposed that the left-hemisphere deficits in processing phonemic information that typically characterise dyslexia (Boets et al., 2013; Brem et al., 2010; Pugh et al., 2000; Vandermosten et al., 2012) would stem from a primary deficit in processing the slow rhythms of speech in the right hemisphere (Goswami, Fosker, Huss, Mead, & Szűcs, 2011; Goswami & Leong, 2013; Lallier et al., 2018, 2017). Supporting evidence for the *transfer* of the oscillatory deficit from the right to the left hemisphere has been provided by a MEG study comparing dyslexic and control readers (Molinaro et al., 2016). In this study, the authors found that, as compared to control readers, dyslexic individuals showed reduced (phase) coherence to the envelope of natural speech within the delta range (0.5-1 Hz) in the right auditory cortex (RAC), but also in the left inferior frontal gyrus (LIFG), an area known to aid phonological processing (Peyrin et al., 2012; Temple et al., 2003). The authors further reported the results of a causal connectivity analysis, according to which delta band oscillatory activity in the LIFG was actually driven by delta activity in the RAC (Figure 1.5). Importantly, the strength of the connectivity between these areas was weaker in the group of dyslexic individuals, and this measure correlated positively with the participants' phonemic awareness. This study provides support to the idea that, most likely through cross-frequency coupling mechanisms, atypical right-hemisphere temporal dynamics of activity within the delta frequency range might be at the roots of the left-hemisphere dysfunction for fast phonemic processing in dyslexia (Goswami, 2011, 2018; Lallier et al., 2018, 2017; Molinaro et al., 2016).

Overall, this evidence suggests a referent role of the perception of the slow rhythms of speech for the acquisition of atypical, but also of typical reading. Nevertheless, all the studies mentioned above compared dyslexic and control readers in transversal designs, missing hence the possibility to establish a causal relationship. To our knowledge, only one longitudinal study following children at familial risk of dyslexia has related pre-reading oscillatory amplitude responses at high frequencies with future reading (De Vos et al., 2017). By contrast, no study until now has provided evidence on the longitudinal (causal) relation between low-frequency sensitivity in terms of phase, both at the neural and at the behavioural level, and typical reading acquisition. This will constitute the main enterprise of this doctoral thesis.

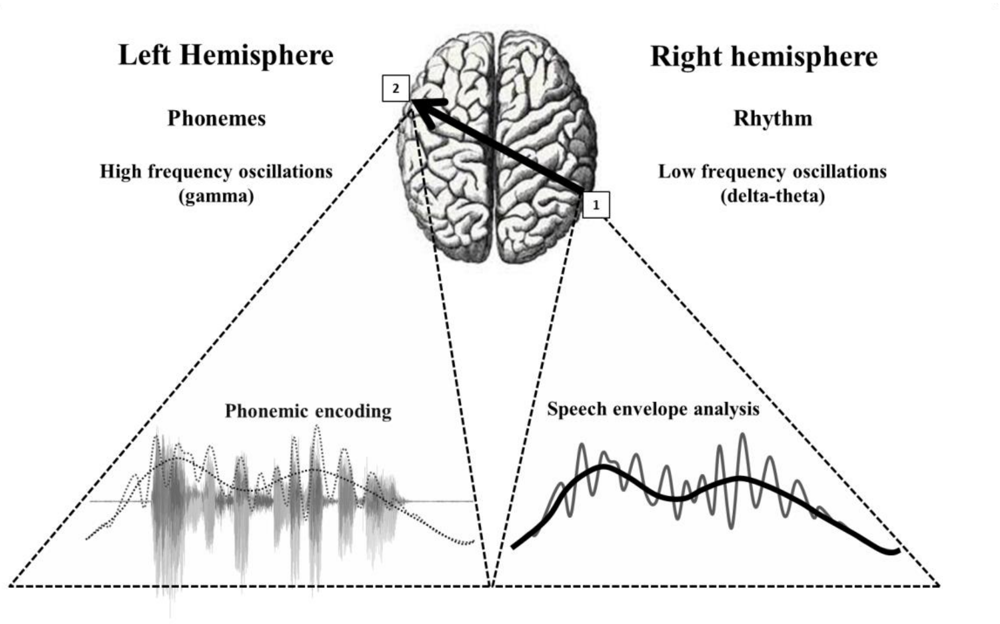

Figure 1.5. Depiction of a putative mechanism for inter-hemispheric connectivity during speech processing. Right auditory areas [1] would encode speech slow temporal modulations at the syllable (theta; dark grey line) and the stress (delta; black line) rates. Parsing the AMs (light grey) of relevant speech units (grey dotted lines) would aid phonemic processing at gamma rates in the left inferior frontal gyrus [2]. Connectivity between [1] and [2] (black arrow) might be reduced in dyslexia (see Molinaro et al. 2016). Taken from Lallier et al. 2017.

Chapter 2: Methodological background

Along this chapter, we will review the relevant methodological aspects upon which this doctoral work is founded. First, a brief overview on the socio-demographic, historical and relevant linguistic features of the Basque language is presented (section 2.1). This is followed by a technical overview (section 2.2) which includes a brief description of electroencephalography (EEG; section 2.2.1), core annotations on brain oscillatory activity and on its value to examine dynamic auditory processing (sections 2.2.2 and 2.2.3) and a short description of *coherence*, the measure used to assess synchronised brain activity to auditory stimuli in the current work (section 2.2.4).

2.1. Brief introduction to the Basque language

2.1.1. Notes on geography, demographics and official status

Basque is a non-Indo-European language spoken mainly at both sides of the Western Pyrenees in a historical socio-geographical area known as *Euskal Herria* (literally, the *Basque Land*). This area comprises two Autonomous Communities in the North of Spain (the Basque Country and the Kingdom of Navarra) and one department in the South of France (the Department of the Atlantic Pyrenees). According to recent statistics (http://www.mintzaira.fr/fr/outils/les-actualites/actualite/article/vieme-enquete-sociolinguistique.html/), Basque is actively spoken by 751,500 individuals in the world. It is estimated that ten thousand people in the world are Basque monolinguals, while the remaining individuals would speak at least one other language. Indeed, in the most common scenario, Basque coexists with other *majority* language(s): Spanish and/or French. This circumstance gives rise to a linguistic particularity, namely that around further 400,000 individuals cannot actively express in Basque, but comprehend it (i.e. these individuals are *passive* speakers of Basque or passive bilinguals Basque-French/Spanish). The interests of Basque and its speakers are safeguarded by the Royal Academy of the Basque Language, created in 1919. Together with Spanish, Basque is a co-official language in the Basque Country and in the Basque-speaking area of the Kingdom of Navarra according to the Spanish Constitution (1978), to the Statute of Guernica (1979) and to article 29 of the Organic Law 13/1982, on the Reintegration and Enhancement of the Foral Regime of Navarra. By contrast, the French Constitution does not recognise but French as the sole official language across the French geopolitical territory. Therefore, from the administrative-political perspective, Basque is the official language of public institutions only in the aforementioned communities within the Spanish territory.

2.1.2. Notes on linguistics

Basque is the only *language isolate* -understood as a natural language for which there is no proven relationship with any other language either currently existing, dead or extinct- in Europe. This is reflected in its particular grammatical, lexical and prosodic properties. Due to their relevance for this doctoral thesis, the rhythmic class, phrasal prosody and writing system particularities of Basque will be shortly discussed.

Traditionally, languages have been grouped in three different rhythmic class categories based on their basic timing units: i) stress-timed (e.g. English); ii) syllable-timed (e.g. Spanish); and iii) mora-timed (Japanese; Abercrombie, 1967). More recent proposals suggest that, instead of constituting absolute categories, languages can be characterised in a rhythm continuum based on the relative distribution of their vocalic and consonantal intervals, and on the variability of consonantal intervals (ΔC; Ramus, Nespor, & Mehler, 1999). Within this framework, Basque would fall in the syllable-time category, at least in respect to its ΔC values (4.41; Molnar, Gervain, & Carreiras, 2014; Ramus et al., 1999).

Regarding phrasal prosody, Basque would belong to languages following a strong-weak (long-short; trochaic) pattern, as opposed to for example English, whose preferred metric would follow a weak-strong (short-long; iambic) pattern. This characteristic is derived from the fact that the syntactic structure of phrases (i.e. the word order within a phrase) is different in Basque and in English. As opposed to languages like English, where the syntactic structure of phrases is ruled by a head-complement (function word-content word) order (e.g. *a book*), the word order within Basque phrases is similar to Japanese, such that the complement precedes the head for the formation of phrases (e.g. *liburu bat* [*book a*]). Interestingly, it has been shown that the head order within phrasal structure originates the cross-linguistic differences in phrasal prosody mentioned above, namely between long-short (typical in Basque) and short-long (typical in English) duration patterns (Gervain & Werker, 2008; Iversen, Patel, & Ohgushi, 2008). Moreover, there is evidence that the phrasal prosody of the native language shapes non-linguistic perceptual tone grouping since infanthood (Molnar, Lallier, & Carreiras, 2014; Yoshida et al., 2010).

Finally, regarding its writing system, the Basque alphabet consists of 27 letters and its orthography is strongly transparent (i.e. there is a simple phoneme to grapheme translation, such as in Spanish or Italian).

2.2. Technical overview

2.2.1. Electroencephalography (EEG)

For almost a century, the electroencephalography (EEG) technique, discovered by Hans Berger in 1929, has allowed neuropsychologists to examine brain function in search of the underlying biological processes that characterise human (and other species) behaviour and cognition. EEG records the electroencephalogram, i.e. the electrical activity of the brain, from electrodes placed on the scalp. EEG is based on a *simple* principle: neurons are excitable cells that communicate with each other through electro-chemical processes (synapses), and such processes generate electrical and magnetic fields that can be recorded at certain distance from the sources (i.e. at the scalp in the case of EEG). Importantly, action potentials themselves are not likely to contribute to the EEG, which is thought to reflect mainly the post-synaptic potentials of synchronised populations of (mostly pyramidal) neurons. As compared to other electrophysiological techniques such as magnetoencephalography (MEG), which is thought to measure only tangentially oriented sources, EEG is suggested to be sensitive to sources of all orientations (Baillet, Mosher, & Leahy, 2001; Cohen & Cuffin, 1991; M. Hämäläinen, Hari, Ilmoniemi, Knuutila, & Lounasmaa, 1993). On the one hand, thanks to its ability to measure current changes in brain sources varying in depth and orientation, together with MEG, EEG is one of the best available techniques to measure temporal processes in the brain to the millisecond resolution. On the other hand, despite the intensive scientific work invested to solve this issue (e.g. Lopes Da Silva, 2004), its spatial resolution is fairly low due to the intrinsic problems that poses the estimation of brain sources from the distribution of electric potentials recorded at the scalp (the *inverse problem*). By contrast, while functional neuroimaging techniques that measure metabolic changes in the brain such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have a low temporal resolution (in the order of seconds), their spatial resolution is notably superior to EEG/MEG. In this sense, while EEG/MEG would measure directly neural activity, PET/fMRI would measure the delayed metabolic consequences of such activity.

The potential of EEG in child psychiatry is enormous, and its applications have been shown in a variety of fields, going from attention, arousal and inhibition to sleep disorders and various cognitive impairments often related to psychiatric conditions such as ADHD or schizophrenia (see Banaschewski & Brandeis, 2007 for a review). Relevant to this doctoral work, EEG has been extensively used to investigate the covert processes of the cognitive and behavioural deficits of children suffering from developmental reading disorders. For example, dyslexic children have been shown to yield attenuated electrophysiological responses to auditory words (Schulte-Körne, Deimel, Bartling, & Remschmidt, 2004), impaired mismatch negativity to subtle speech and auditory frequency deviance (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999) or abnormal response to print (Maurer et al., 2007). This evidence suggests that EEG is an appropriate technique to capture the variance of language development in children and detect early abnormalities in language-related functions.

2.2.2. The use of brain oscillatory activity to measure linguistic processing

Traditionally, studies examining language processing have measured electrical responses time-locked to the stimulus and used multi-trial averaging techniques to extract the EEG from the background noise (event-related potentials or ERPs). Although ERPs can help disentangling a great variety of brain sub-processes related to language (e.g. Kutas & Hillyard, 1980), their analysis is reduced to activity that is time-locked to the stimulus, eclipsing thus the study of the duration and rate of the activity that is not phase-locked to an external event (Pfurtscheller & Lopes da Silva, 1999). Due to this, ERPs have been considered only as a rough estimate of brain activity (Başar, 1999). By contrast, brain oscillatory analysis allows examining both evoked and induced (non-phase-locked) activity (see Fig 2.1), reason for which, among other that will be discussed below, its use has increased considerably at the cost of ERPs analyses in the neurocognitive science of language field in the past two decades (e.g. Bastiaansen & Hagoort, 2006; Weiss & Mueller, 2003).

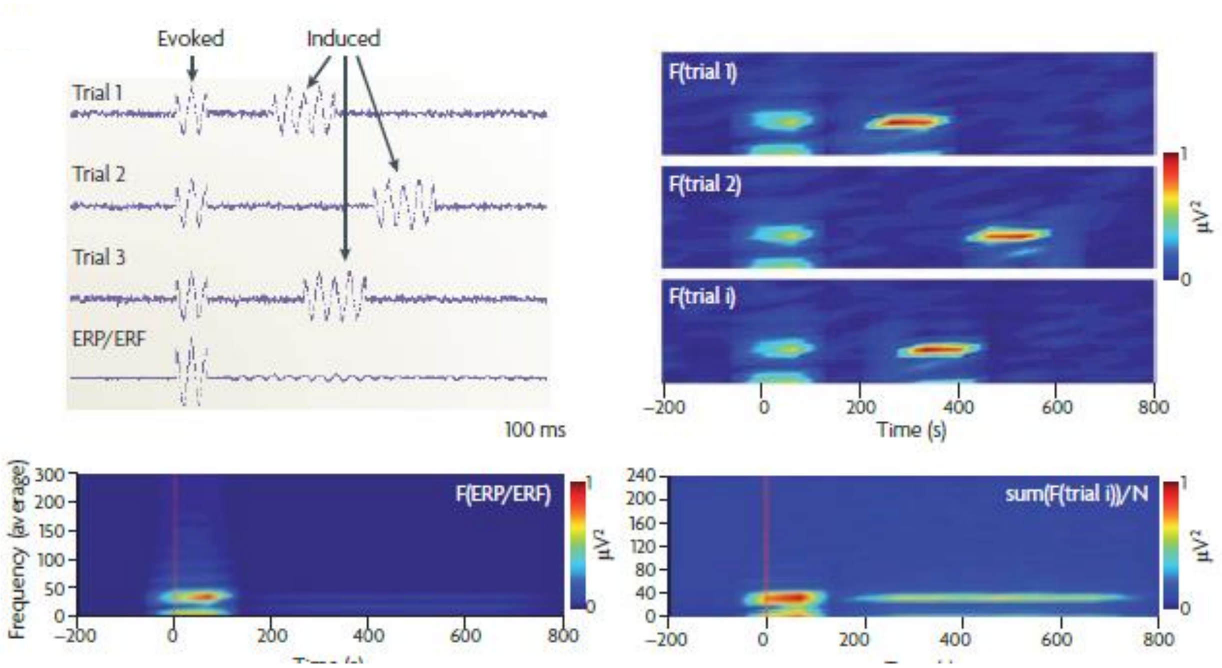

Figure 2.1. Illustration of the difference between ERP/ERFs and time-frequency analyses. The left top panel shows the electrophysiological recordings across three different trials and the average across them (ERP/ERF). The bottom left panel depicts the time-frequency map of the ERP/ERF, where only the evoked response is visible. By contrast, the right top panel shows three single trial (not averaged) time-frequency maps. The bottom right panel shows the average of the single trial time-frequency maps, where both evoked and induced activity can be seen. Adapted from Uhlhaas and Singer (2010).

Another key difference between time-frequency assessment of oscillatory activity and ERPs is that, unless specifically assessed, ERP analyses consist of averaging the brain signal across its frequency components. By contrast, oscillatory analyses allow by definition the individual assessment of different frequency bands. Accordingly, brain oscillations have been broadly subdivided into five frequency bands: delta (<4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz) and gamma (>30 Hz). Different frequencies have been related to different cognitive functions and, although their specific contributions are still a matter of ample debate, wide evidence supports that they can contribute differently to diverse aspects of language processing (Bastiaansen & Hagoort, 2006; Weiss & Mueller, 2003). Importantly, brain oscillations, or the analysis of their integration, offer an adequate way to investigate a long elusive problem in the field of psycholinguistics, namely the *binding problem*. For language acts to be experienced as a unity, it is necessary for the brain to integrate auditory perception and diverse levels of language processing (phonological, morpho-syntactic, semantic, pragmatic and prosodic). The fact that oscillatory analysis allows us to *decompose* the brain signal suggests that this could be a far superior method to examine the dynamics of language processing as opposed to ERPs, which would obscure these differences by averaging the different frequency components.

2.2.3. Different measures of brain oscillatory activity: Amplitude vs. phase measures

The brain signal is a complex signal that can be artificially decomposed in multiple waveforms. Any waveform can be described by three parameters: its *amplitude*, its *phase* and its *frequency* (see Fig. 2.2). The amplitude of a waveform corresponds to the signal energy changes along the vertical axis. In the field of EEG, the amplitude value is commonly squared to obtain the *power* measure. By contrast, the phase of a waveform is the exact position of the oscillation at a moment in time with respect to a reference (usually the zero) point. As a measure of position, phase is expressed in degrees and can therefore vary between 0 and 360 degrees. Accordingly, the position of an oscillation in a precise moment can always be described in terms of phase or phase shift. The interval required for the waveform to return to its initial value is known as a cycle. Finally, frequency would be the number of times that the signal repeats itself in one second (i.e. the number of cycles per second) and is expressed in Hertz (Hz).

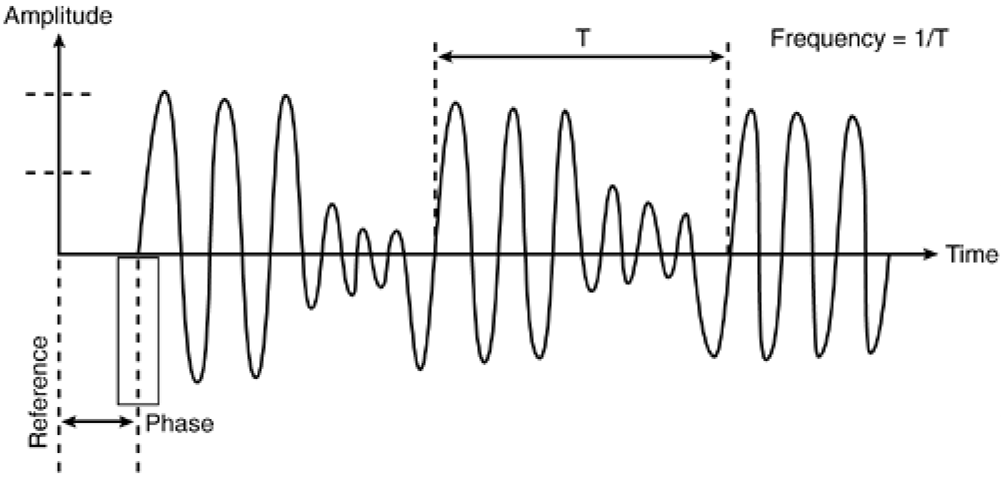

Figure 2.2. Depiction of the amplitude, phase and frequency features of a waveform

Since the linguistic acoustic signal is also a complex waveform (see section 1.1), the joint time-frequency analysis of the brain and the linguistic signal allows us to examine the behaviour of the brain waves with respect to the external auditory signal. Interestingly, it has been shown that brain waves *entrain* (i.e. synchronise) to external stimuli at different frequencies both in terms of amplitude and phase. Although the functional relevance of such entrainment is yet a matter of ample debate, different roles have been proposed for the amplitude and phase synchronization phenomena. On the one hand, amplitude changes have been suggested to measure local changes in the activity of populations of neurons (Nunez & Silberstein, 2000). These changes have been consistently associated with different cognitive processes such as the construction of objects representations (Tallon-Baudry & Bertrand, 1999), cognitive performance (Hanslmayr, Sauseng, Doppelmayr, Schabus, & Klimesch, 2005), visual attention (Thut, Nietzel, Brandt, & Pascual-Leone, 2006) or visual discrimination (van Dijk, Schoffelen, Oostenveld, & Jensen, 2008). On the other hand, the phase coherence phenomenon is suggested to emerge due to the synchronization of the firing patters of neural populations located at distant sites in the brain (inter-areal synchrony; Varela, Lachaux, Rodriguez, & Martinerie, 2001), and it has been suggested that communication between different brain areas could actually occur through phase coherence (Fries, 2005). Phase synchronization has been related with an ample variety of cognitive phenomena, from visual perception (Busch, Dubois, & VanRullen, 2009; Mathewson, Gratton, Fabiani, Beck, & Ro, 2009), to anticipation (Stefanics et al., 2010) and perceptual and attentional variability (VanRullen, Busch, Drewes, & Dubois, 2011). Both amplitude and phase seem hence to be relevant and adequate measures to explore neural dynamics for coding external stimuli, and there is evidence that they can be used as complementary measures (Schyns, Thut, & Gross, 2011).

Relevant for our field, brain waves also entrain to the different temporal components of the speech signal, and synchronization has been found both in terms of phase and of amplitude (e.g. Ahissar et al., 2001; Gross et al., 2013; Molinaro et al., 2016; Peelle et al., 2013). Nevertheless, recent studies in the field of language have reported that phase could be a more informative measure as opposed to amplitude when auditory processing is concerned (Howard & Poeppel, 2010; Luo & Poeppel, 2007; Ng, Logothetis, & Kayser, 2013). For example, a study measuring macaques' local field potentials in response to natural animal sounds with intracranial recordings reported that neural firing patterns with selective response to the stimulus were reflected on the phase and not on the amplitude of oscillations, and such results were replicated in humans measuring scalp EEG (Ng et al., 2013). This evidence supports the idea that the precise timing of the oscillations (i.e. their phase) could be a more valid index to study stimulus-selective response for auditory (linguistic) processing as opposed to amplitude changes. Accordingly, phase coherence was systematically used in this work to measure brain synchronization to the different auditory stimuli studied through this work.

2.2.4. Coherence as a measure of synchronised activity during auditory processing

To calculate the relation (dependency) between the phase of the brain and of the speech signals, we calculated *coherence* following the method proposed by Halliday et al. (1995). This method is a version of the Pearson correlation in the frequency domain and quantifies the degree of coupling between to signals $x(t)$ and $y(t)$. Its output is a number between 0 and 1 (no linear and perfect linear relation, respectively) for each frequency. Coherence is computed by dividing the squared cross-spectrum of the signals $x(t)$ and $y(t)$ by the product of their power spectra as follows:

$$Coh_{xy}(f) = \frac{\left|P_{xy}(f)\right|^2}{P_{xx}(f)P_{yy}(f)}.$$

In the field of auditory neuroscience, it is common practice to calculate the dependency (coherence) between the brain signal and an auditory external signal of reference (e.g. x(t): EEG signal; y(t): audio signal). In this doctoral thesis, coherence was calculated between the brain signals and the envelope of speech at different frequencies (Experiment 1) and between the brain signals and the envelope of non-linguistic acoustic signals amplitude-modulated at different rates (Experiment 2).

Chapter 3: The current research work

In the current chapter, we first present our main research aims and research questions (section 3.1), followed by a detailed description of the participants that took part in this study (section 3.2). In section 3.3, for parsimony reasons, some methodological aspects of the behavioural tasks that were used in more than one of the experiments that constitute this thesis are presented, together with the description of the technical aspects of the EEG recording. Finally, section 3.4 presents preliminary steps for analysing the reading performance of the children prior to its use throughout this doctoral thesis' experimental works.

3.1. Research aims

The main aim of this doctoral thesis was to examine the cross-sectional and longitudinal contribution of rhythmic processes at the neural and at the behavioural level to reading acquisition. To this aim, we recruited a cohort of Basque-speaking pre-school children who took part in a longitudinal project that lasted two full years. Testing was carried out at three different time points allocated right after the end of the school year: after the second-to-last year of pre-school (T1; four-to-five years old), after the last year of pre-school (T2; five-to-six years old) and after Grade 1 (T3; six-to-seven years old). At each testing time, we used EEG to measure brain rhythmic (oscillatory) activity synchronised to natural language and to auditory stimuli modulated at rates relevant for speech perception. Together with the EEG measures, we tested the children's behavioural rhythmic skills and also run a battery of tasks measuring classical reading predictors. Relevant for this study, in the Basque Country formal reading instruction is first introduced in the school curriculum in Grade 1, and hence the children who participated in this study learned to read formally in the interval between T2 and T3. Consequently, reading skills were only assessed in the final testing time of this project (T3).

Research questions

The aims explained above led us to materialise four main research questions to which we will try to give an answer in the different experiments presented along this thesis:

1. **How does oscillatory activity in response to speech and to auditory stimuli modulated at rates relevant for speech perception develop during childhood? (Experiments 1 and 2, respectively)**
2. **What is the contribution of brain oscillatory activity to reading acquisition? (Experiment 3)**
3. **What is the contribution of rhythmic behavioural skills to reading readiness and later reading acquisition? (Experiment 4)**

4. **Can we use brain and behavioural rhythmic sensitivity measures as *equivalent* for the prediction of reading achievement? (Experiment 5)**

3.2. Materials and methods

3.2.1. Participants

The children who participated in this longitudinal study were recruited from two different public schools in Donostia-San Sebastián (Basque Country, Spain). The Basque Country is a bilingual community in which Spanish and Basque coexist as official languages. Education at school is provided in three different models: model A (Basque only), model B (bilingual Basque-Spanish) and model D (Spanish only). All children in our sample received formal education in the model A variant. Relevant to this doctoral work, this meant that they received formal reading instruction in Basque only. Nevertheless, at home they spoke either Spanish, Basque or both (none of the parents reported speaking any other language at home). Due to the importance of the home language in the constitution of the individual's psycholinguistic profile, language dominance was assessed through the expressive vocabulary section of the BEST (Basque English and Spanish Test), a test created specifically at BCBL for assessing participants' multilingualism (de Bruin, Carreiras, & Duñabeitia, 2017). The decision on the individual child's language dominance was supported by a short interview with the experimenter and by a subjective language questionnaire that the parents/tutors were asked to fulfil. A detailed description of these three measures is available in the Appendix (section A1). The final language dominance measure was used to discard effects of this variable on the results of the linguistic tasks presented in this whole doctoral thesis. Information on the psycholinguistic profile of the children is provided in the general description of the participants, and throughout this whole research work when relevant.

Children were matched in parents' or tutors' socioeconomic status (SES) based on their yearly net income (medium or medium-high). Demographic information at the individual level is provided in Table 3.1.

Table 3.1. Participants' demographic information

Subj	Gender	Hand	Age T1	Age T2	Age T3	SES
1	M	R	5.50	6.25	7.58	Md
2	M	R	5.17	6.00	7.08	Md
3	F	R	4.92	5.75	6.83	Md-H
4	M	R	4.75	5.67	6.58	Md-H
5	F	L	5.50	6.42	-	Md
6	M	R	5.00	5.83	6.83	Md
7	M	R	5.50	6.33	7.50	Md
8	M	R	5.25	-	-	Md
9	M	R	5.00	5.75	7.08	Md
10	F	R	4.75	5.75	6.75	Md
11	F	R	4.67	5.42	6.67	Md
12	F	R	4.67	5.50	-	Md
13	F	R	4.67	5.42	6.58	Md
14	F	R	4.67	5.50	-	Md
15	M	R	5.50	6.42	7.50	Md
16	F	R	5.42	6.25	7.25	Md
17	F	R	4.67	5.50	6.58	Md
18	M	R	5.50	-	-	Md
19	M	R	5.50	6.42	-	Md
20	M	L	5.17	6.00	7.00	Md-H
21	M	R	4.83	5.67	6.75	Md
22	M	R	4.67	5.50	6.50	Md
23	M	R	4.75	5.50	6.58	Md
24	M	R	5.50	6.33	7.33	Md

25	F	R	5.17	5.92	7.17	Md
26	M	L	4.83	5.67	6.67	Md
27	F	R	5.42	6.08	7.33	Md
28	M	R	4.92	5.75	6.75	Md
29	M	R	5.17	5.83	7.08	Md
30	F	R	5.17	6.08	-	Md
31	F	L	5.33	6.33	7.25	Md
32	M	R	4.92	5.75	6.83	Md
33	M	R	4.58	-	-	Md
34	F	R	5.33	5.92	7.17	Md
35	F	R	4.92	-	-	Md
36	F	L	5.42	6.25	7.25	Md
37	F	R	5.08	5.83	6.83	Md
38	F	R	4.67	5.58	6.50	Md
39	F	R	5.42	5.17	7.33	Md
40	F	R	5.50	6.33	7.42	Md
41	M	R	5.00	5.75	6.75	Md-H
42	M	R	5.25	6.00	6.92	Md

F = Female; Hand = Handedness; M = Male; Md = Medium; Md-H = Medium-high; SES = Socioeconomic status; Subj = Subject

Children for whom age information at T2 and/or T3 is not available because they did not participate in the corresponding testing time are marked with a hyphen (-).

No cognitive anomaly was evident in any of the children during the two years that the current study lasted. Parents reported children’s normal hearing and normal or corrected-to-normal vision. None of the children had a family history of developmental language disorder, and they were not at familial risk of any other cognitive-related genetic pathology, as reported by the parents. Importantly, as revealed by objective reading measures, none of the children included in this study seemed to suffer from any reading-related developmental pathology (see section 3.2.4 below).

Children were tested under signed parental authorization at each of the testing times, and the whole longitudinal experiment was approved by the BCBL Ethics Review Board and complied with the guidelines of the Helsinki Declaration.

T1

Forty-two children were tested in the first phase of the study (age *M* = 5.09 years; *SD* = .31; range: 4.58-5.50; 22 males). Twenty-nine of the children were characterised as Basque dominant and 13, as Spanish dominant. Five of the children were left-handers.

T2

Thirty-eight children came back for testing one year later (age *M* = 5.88 years; *SD* = .34; range: 5.17–6.42; 19 males). Twenty-six and 12 of the children were defined as Basque or Spanish dominant, respectively. Five of the children were left-handers.

T3

The last sample of the study was formed by 33 children (age *M* = 6.98 years; *SD* = .32; range: 6.50-7.58; 18 males). Twenty-two and 11 children were characterised as Basque or Spanish dominant, respectively. Four of the children were left-handers.

3.2.2. Stimuli and procedure

In T1 and T2, the behavioural and the EEG sessions took place in different days to avoid children's fatigue. Maximum distance between the testing days was of one month. All children performed the behavioural tasks (approx. 1 hour) at day 1 of testing and the EEG tasks (approx. 1.5 h) at day 2 of testing. In T3, children performed the behavioural and EEG tasks in the same day (approx. 2 hours). Children were allowed to take breaks when desired, and they received a gift after each of the testing sessions as a sign of our gratitude for taking part in the study.

3.2.2.1. Behavioural battery

The battery of behavioural tasks was similar across the three testing times, but children completed two more tasks at T3 according to their increasing linguistic competence (a working memory task and the reading tasks). In the interest of clarity, a summary of the tasks that the children run across the years is provided in Table 3.2.

Table 3.2. Summary of the behavioural tasks completed by the children across the testing times

	Task	**T1**	**T2**	**T3**
Neuropsychological screening	Matrices (WPPSI-III)	✔	✔	✔
Reading predictors	RAN (colours)	✔	✔	✔
	Pseudoword repetition	✔	✔	✔
	Letter name knowledge	✔	✔	✔
	Beat synchronization	✔	✔	✔
	Phoneme deletion/elision	✔	✔	✔
	Digit span backward	-	-	✔
Reading	Word and pseudoword reading	-	-	✔
	Text reading	-	-	✔

Each of these tasks is described in the *Materials and methods* section of the corresponding experiment. Nevertheless, for parsimony reasons, the neuropsychological and the reading tasks, which are recurrently used in the different chapters of this doctoral dissertation, will be presented here and referenced throughout the text when necessary.

3.2.2.1.1. Neuropsychological screening: IQ assessment

The Matrix reasoning subtest from the WPPSI-III (Wechsler, 2002) was used to obtain a measure of non-verbal IQ in each of the testing times (T1, T2 and T3). Children were presented with a matrix of three drawings and a blank square, and asked to complete the series with the correct element out of four to five alternatives. The test consisted of a total of 29 items, and the initial item was adapted upon the child's age. This task lasted approximately ten minutes. Direct scores were converted into scalar (standardised) scores to correct for children's age differences (in months) and for comparability across testing times.

3.2.2.1.2. Reading assessment

At T3, two tasks were used to measure two different aspects of reading: Word and pseudoword reading and Text reading.

3.2.2.1.2.1. Word and pseudoword reading

Stimuli were presented in the centre of the screen in capital letters in Arial font size 44. Children were instructed to read as fast as possible minimizing mistakes, and the next item was not displayed until they produced an answer. Stimuli consisted of 20 high-frequent words (List 1) and 20 pseudowords (List 2). Pseudowords were created changing one phoneme of an existing high-frequent word (e.g. *LIBUKU from LIBURU [book*]*).Within each category, stimuli varied in length, such that 10 items were bi-syllabic, and the 10 remaining items were tri-syllabic. Five of the items in each condition were formed by syllables with a consonant-vowel structure (e.g. bi-syllabic: *KATU* [cat]; tri-syllabic *HARAGI* [meat]), while the remaining five contained one syllable with a consonant cluster (e.g. bi-syllabic: *PRAKA* [trousers]; tri-syllabic *TEKLATU* [keyboard]). Total reading time and errors were recorded for each list, and two separate per minute efficiency measures were calculated as follows:

$$\text{Item reading efficiency} = \frac{\text{Total number of correct read items}}{\text{Total time}} * 60$$

where *Item* was Word or Pseudoword, correspondingly.

3.2.2.1.2.2. Text reading

Participants were asked to read a short passage from the novel *El Principito* (*The little prince*, written by Saint Exupéry) translated into Spanish and adapted from Lallier, Valdois, Lassus-Sangosse, Prado, and Kandel (2014). The text consisted of 85 words and seven lines. Participants were instructed to read fast, but with as few mistakes as possible. Time (in seconds) and number of errors were recorded. Maximum reading time allowed was 300 seconds (5 minutes). For children who exhausted this time, the number of read words was also recorded. With the time and the errors measure, we calculated the following reading efficiency index:

$$\text{Text reading efficiency} = \frac{\text{Total number of correct read words}}{\text{Total time}} * 60$$

3.2.2.2. EEG recording

In this section, the general practices for EEG data recording are presented. The stimuli and procedure for the EEG tasks will be described in the corresponding experiments along this doctoral work.

The EEG of the children was recorded in a child-friendly soundproof electrically-shielded room. Children were comfortably seated in a chair adapted to their size and approximately 30 cm away from the CRT computer screen. They were instructed to stay silent and move as least as possible. The EEG signal was recorded using a Brain Products GmbH actiCAP with 32 electrodes. Electrodes FC5, FC1, FC2, FC6, CP5, CP1, CP2 and CP5 were not included to reduce preparation time and avoid children's fatigue. Accordingly, 19 electrodes (FP1, FP2, F7, F3, Fz, F8, F4, C3, Cz, C4, T7, T8, P7, P3, Pz, P8, P4, O1 and O2) were distributed over the scalp based on 10-10 International System. Additional reference electrodes were placed in both mastoids A1 and A2, in electrode FCz and around the eyes at left Heog, the right Heog and the left Veog. Sampling rate for data acquisition was set at 500 Hz, and an online band-pass filter from 0.1 to 1000 Hz was applied. Monopolar differential recording was referenced online to electrode FCz. Impedance was kept under 10 kΩ for the scalp electrodes and under 15 kΩ for reference and EOG electrodes.

3.2.3. Data analysis

This section describes general practices for the analysis of the data that are recurrently used throughout this doctoral work.

3.2.3.1. Outlier treatment

Given our modest sample size and in consideration of the naturally variable performance of very young children, we did not remove *a priori* outliers based on their score in respect to a group central value (e.g. median, mean). Instead, data were systematically visualised after each statistical analysis to detect possible spurious results driven by extreme observations. When such was the suspicion, we performed our analyses both with and without the extreme observation(s) and, in case of a notable difference, both results are presented. Nevertheless, we did screen the data to spot children whose performance decreased inexplicably from year to year (*longitudinal* *outliers*). Such observations were removed when they affected significantly the test-retest reliability of the corresponding task.

3.2.3.2. Statistical tests

As mentioned above, some of our children were left-handers. Asymmetries for processing the temporal information of acoustic signals do not seem to be influenced by hand dominance (Abrams et al., 2009), but as a safety check, we performed all analyses involving brain measures with and without these children. Unless otherwise stated, there were no differences between the results of the analyses with and without these participants.

Our decision not to remove outliers before statistical analyses led us to systematically conduct outlier resistant non-parametric methods to ensure that our tests were not contaminated by extreme observations. Accordingly, the following statistical tests were used depending on the analysis concerned.

Linear regression

To estimate linear regression in an outlier-robust manner, we used function *R'*s function *lmrob()* from package *robustbase,* based on contemporary algorithms for the estimation of linear regression models in data sets with extreme observations (Maronna, Martin, & Yohai, 2006).

Linear correlation

Spearman's ranked correlations were used to estimate pair-wise correlation coefficients. Due to the relevance of the differences in age and IQ at these young ages, before performing any correlation analyses we first calculated a robust linear model (using the function *lmrob* introduced in the *Linear regression* section) with age and IQ as single predictors. Note that, in principle, besides controlling for age and IQ in our correlation analyses, we also considered controlling for the factor Language dominance (Basque vs. Spanish) to ensure that this variable did not play a fundamental role, especially in the linguistic tasks. Nevertheless, the Language factor measure did not capture any significant variance in any of the robust linear models (with age, IQ and Language dominance as predictors) calculated prior to the computation of the partial Spearman correlations (all *p*s >.30). In order to confirm that Language dominance was not related to any other variable measured in this study, we computed separate pair-wise comparisons between the Language dominance task and the behavioural and EEG tasks used across this research work. Results showed that none of the tasks correlated significantly with the Language dominance measure (all *p*s >.20). Due to this, this factor was dropped to avoid losing degrees of freedom and statistical power. It is important to highlight that this result is not surprising, since all children received formal school instruction in Basque, and all of them were fluent in this language.

Accordingly, the results (residuals) of the regression analyses with age and IQ as sole predictors were then entered into the respective correlation analyses. Consequently, all the correlations presented along the current work are partial Spearman correlations controlling for IQ and age. In the interest of parsimony, the short form partial Spearman correlations will be used thereafter.

Group comparison

Non-parametric methods were used to perform median (instead of mean) comparisons (Mann-Whitney t-test). Furthermore, when covariates where included in the analysis, non-parametric ANCOVAs were computed. For the latter, we used *R*'s function *sm.ancova()* contained in package *sm* (Bowman & Azzalini, 2014). This function uses smoothing techniques to statistically compare regression lines which do not comply with normality requirements (Bowman & Azzalini, 1997; Bowman & Young, 1996; Young & Bowman, 1995). This analysis yields an *h* measure (and an associated *p*-value), which estimates the dissimilarity between the regression lines compared.

Linear mixed models

When longitudinal analyses were involved, we implemented linear mixed models analyses using the *lme4* package available in R (Baayen, Davidson, & Bates, 2008; R Core Team, 2017). We chose this statistical test for two main reasons. First, the random effects by subject help to control for individual variability, reducing hence the weight of extreme observations for the calculation of group level statistics. Second, it has been recurrently suggested that this is the optimal currently available model fitting technique for longitudinal designs with missing data (e.g. Garcia & Marder, 2017; Laird & Ware, 1982).

Regarding the selection of the fixed effects, we used maximum likelihood (ML) estimation to fit several models and decide which fitted the data best. ML allows comparing fits with identical random effects but different nested fixed effects (Zuur, Ieno, & Elphick, 2010). Model selection was then based on the comparison of the respective model's Akaike information criterion (AIC), maximum log likelihood units, on visual inspection of the coefficients (Gelman & Hill, 2006), and supported by our *a priori* hypotheses.

Concerning the construction of the random effects, by-subject slopes for the within-subject factors were entered to control for within-subject variability and measures' interdependency. From there, the complexity of the random effects structure was increased in a series of models leading to a maximal model that converged and contained only the random effects that increased significantly the residual variance captured by the model (Barr, Levy, Scheepers, & Tily, 2013).

Although parameters were estimated with ML for model comparison, the final model parameters were estimated with restricted maximum likelihood (REML), since its estimation of the random effects improves when small sample sizes are involved as compared to ML (e.g. Morrell, 1998). We used the *R* package *lsmeans* (Lenth, 2016) to extract the model's least square means (estimates), standard errors and confidence levels at .95 for each of the levels of the factors (and interactions) included in the fixed effects. Lastly, the *lsmeans* package was also used to explore post-hoc contrasts. This package uses the Satterthwaite method to estimate *t*-values, and their associated *p*-values are corrected for multiple comparisons using the Tukey HSD method.

3.2.4. Reading data: Preliminary analyses and results

In this section, preliminary steps implemented on the reading data will be presented. The aim of these preliminary analyses was twofold. First, our intention was to reduce the multiple reading measures into a single measure for its later use along the different experiments described in this research work and hence reduce the number of comparisons. Second, since this study was aimed at testing reading acquisition in typically developing children, before using our reading measures for any other analysis, we ensured that none of the children's scores deviated excessively from the mean of the group and hence discard that reading acquisition could be hampered in any of the children, at least at this young age.

3.2.4.1. Reading data analysis

First, an efficiency measure was calculated for each of the single item reading subtasks (Word reading efficiency and Pseudoword reading efficiency) and for the Text reading task (Text reading efficiency) following the procedure explained in section 3.2.2.1.2 of the current chapter. The data were then converted into *z*-scores to facilitate comparison across tasks.

In order to ensure that all the reading tasks were highly correlated and reduce the scores to a single measure, first we calculated a Spearman partial correlation between the Word reading and the Pseudoword reading subtasks. Thereafter, a second partial Spearman correlation between the Word and pseudoword reading and the Text reading tasks was computed. The threshold for averaging the tasks was set at $\rho > .80$.

Data were finally screened to detect children whose performance in the reading task(s) deviated more than 3 *z*-scores from the group to ensure that none of the children had reading-related issues (up to the testing moment).

3.2.4.2. Reading data results

As expected, the Word reading and the Pseudoword reading subtasks correlated highly ($\rho = .92$; $p < .001$), and they were hence averaged. Similarly, the correlation coefficient between the Text reading task and the Word and pseudoword reading task was high ($\rho = .83$; $p < .001$). Therefore, a composite Reading measure was created averaging both (Reading composite). Table 3.3 shows the individual efficiency z-scores for the different tasks and for the final composite measure. *Z*-scores in the reading tasks did not suggest the presence of abnormal reading development in any of the children, at least at this initial stage (*z*-score range: -1.22 to 1.96). Hence, all the children's reading data were included in later analyses.

Table 3.3. Individual *z*-scores of the children in the reading tasks. The last column shows the *z*-scores in the Reading composite measure (the average between the Word and Pseudoword reading and the Text reading tasks)

Subj	W/PW	Text	Composite
1	-.21	-.75	-.48
2	.58	.18	.38
3	2.00	1.91	1.96
4	-.78	.13	-.32
5	-	-	-
6	-.31	-.69	-.50
7	-1.54	-	-
8	-	-	-
9	.04	-.92	-.44
10	-1.24	-1.21	-1.22
11	.79	2.04	1.41
12	-	-	-
13	-.23	-.75	-.49
14	-	-	-
15	-.43	-.54	-.48
16	1.50	1.15	1.33
17	.63	.78	.71
18	-	-	-
19	-	-	-
20	-1.16	-1.02	-1.09
21	.60	.67	.63
22	-1.25	-.84	-1.04
23	.23	-.87	-.32
24	1.21	1.3	1.26
25	-.51	-.83	-.67
26	-1.66	-	-
27	1.38	1.40	1.39
28	-1.11	-1.17	-1.14
29	-.66	.04	-.31
30	-	-	-
31	1.15	.39	.77
32	-.38	-.09	-.24
33	-	-	-
34	0	.12	.06
35	-	-	-

36	1.19	1.73	1.46
37	.90	-.15	.37
38	-.58	-.80	-.69
39	-.78	-1.12	-.95
40	1.16	.64	.90
41	.22	.07	.15
42	-.74	-.8	-.77

Subj = Subject; W/PW = Word and pseudoword

Subjects for which no data are available because they did not complete the tasks at T3 are marked with a hyphen (-).

Chapter 4: Longitudinal trajectory of coherent brain oscillatory activity in response to auditory stimuli and its contribution to reading development

In spite of the accumulating evidence supporting the relevant role of brain phase coherent activity for speech perception (Bourguignon et al., 2013; Gross et al., 2013; Howard & Poeppel, 2010; Peelle et al., 2013; Zion Golumbic et al., 2013) and its contribution to reading skills (J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Molinaro et al., 2016; Power et al., 2016, 2013), no study yet has explored the development of this activity from the longitudinal perspective, nor strived to examine its prospective relation with reading skills. This chapter will address these issues in three different experiments whose scope can be best summarised with our first two research questions, namely

- **Research question 1: How does oscillatory activity in response to speech and to auditory stimuli modulated at rates relevant for speech perception develop during childhood? (Experiments 1 and 2, respectively)**
- **Research question 2: What is the contribution of brain oscillatory activity to reading acquisition? (Experiment 3)**
- Research question 3: What is the contribution of rhythmic behavioural skills to reading acquisition? (Experiment 4)
- Research question 4: Can we use brain rhythms and behavioural rhythms as *equivalent* measures for the prediction of reading achievement? (Experiment 5)

4.1. Experiment 1: The development of coherent oscillatory activity in response to natural speech

4.1.1. Introduction

In non-pathological adult populations, the phase of the brain signal at low-frequency bands (theta band: 4-8 Hz; and delta band: <4 Hz) aligns with the phase of the slow components of the amplitude envelope of speech in a phenomenon that can be described as *brain-to-speech coherence* (Bourguignon et al., 2013; Giraud & Poeppel, 2012; Gross et al., 2013; Peelle & Davis, 2012; Poeppel, 2003). Brain-to-speech coherence has been correlated with relevant linguistic operations such as the processing of intelligible versus unintelligible signals (Bourguignon et al., 2013; Gross et al., 2013; Molinaro & Lizarazu, 2018; Peelle & Davis, 2012) or the segregation of a target linguistic signal in cocktail-party situations (Ding & Simon, 2012a; Ding, Chatterjee, & Simon, 2014; Fuglsang, Dau, & Hjortkjær, 2017; Zion Golumbic et al., 2013). Furthermore, abnormal brain-to-speech coherence has been found in children and adults with language disorders such as dyslexia, which reinforce the idea that appropriate temporal synchronization to speech could be crucial for attaining proper language skills (Goswami, 2011; Lallier et al., 2017; Molinaro et al., 2016; Power et al., 2016). Theoretical accounts that aim to explain the functional role of entrained oscillatory activity in the brain as the *asymmetric sampling in time* hypothesis (AST; Poeppel, 2003) have suggested that brain-to-speech coherence would code for the prosodic (*rhythmic)* information of the linguistic signal, and hence would show a right hemisphere bias. Indeed, several studies have shown that brain-to-speech coherence is stronger in the right than in the left hemisphere (Bourguignon et al., 2013; Gross et al., 2013; Molinaro et al., 2016). By contrast, phonemic information (i.e. information at fast rates) would be preferentially processed in the left hemisphere or bilaterally (Boemio et al., 2005; Poeppel et al., 2008). Supporting this, there is evidence that gamma band (>30 Hz) oscillatory tracking occurs preferentially in the left hemisphere (Boemio et al., 2005; Gross et al., 2013; Poeppel et al., 2008). Several research works have suggested that the integration of speech information at fast and slow rates would occur thanks to the orchestration of low-frequency bands, such that the *slow rhythm(s)* of speech -originated foremost from the amplitude fluctuations of syllables and phrasal prosody units- would be the *acoustic landmarks* upon which fast oscillatory sampling, necessary for the processing of phonemic contrasts, would rely (Doelling et al., 2014; Ghitza, 2011; Giraud & Poeppel, 2012).

Surprisingly, and despite the remarkable functional relevance that the brain-to-speech coherence measure might have for language development, no study has yet targeted specifically its development during childhood. The attempts to characterise the neural system supporting speech perception at birth and along development have though yielded relevant preliminary findings on which to base predictions on the emergence of the brain-to-speech coherence phenomenon. It is known that human babies process speech in a differential (and preferential) manner as compared to other non-linguistic acoustic signals even before being able to produce speech themselves (Ramus et al., 2000; Vouloumanos & Werker, 2007). Relevant to our study, consistent evidence has shown that the new-born's brain already shows hemispheric specialization for different spectral and/or temporal features of speech (Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002; Homae, Watanabe, Nakano, Asakawa, & Taga, 2006; Peña et al., 2003; Perani et al., 2011; Telkemeyer et al., 2009). Homae et al. (2006) tested three-month old babies with NIRS and showed that sentences with prosody elicited more hemodynamic changes in right temporo-parietal areas as compared to sentences without prosody (i.e. without pitch contour). Similar results have been reported from research testing two-days old infants (Perani et al., 2011). Although these studies are in line with the right-lateralised pattern for the slow components of speech found in adults, they examined changes in the hemodynamic response (NIRS/fMRI), and the comparison with the adults studies, which are usually performed with EEG or MEG, should be performed with caution given the different temporal resolution of the techniques and the different biological processes underlying the responses measured (Nunez & Silberstein, 2000). Unfortunately, the attempts to find electrophysiological responses to stimuli modulated at different temporal rates at birth have not been successful (Telkemeyer et al., 2009), probably because discontinuous EEG in very young infants does not allow to perform adult-like analyses (Hoogenboom, Schoffelen, Oostenveld, Parkes, & Fries, 2006; Koch, Werner, Steinbrink, Fries, & Obrig, 2009). Indeed, to our knowledge, only two studies have successfully performed a time-frequency analysis to measure the synchronization of oscillatory responses in infants (Peña, Pittaluga, & Mehler, 2010; Telkemeyer et al., 2011). In the study by Peña et al. (2010), the authors showed that at six months, full-term infants showed increased gamma power when exposed to their native language (Spanish) as compared to two foreign languages (Japanese and Italian). Telkemeyer et al. (2011) tested three and six months old infants and compared their oscillatory responses to non-linguistic auditory signals modulated at fast (phonemic) as compared to slow (syllabic/prosodic) rates. The authors reported a developmental change in the perception of prosody during this period, since six- but not three-month olds showed theta-band (4-8 Hz) power desynchronization after 500 ms of stimulus presentation for sounds modulated at slow rates as compared to stimuli modulated at fast rates (Telkemeyer et al., 2011). It is important to highlight that none of these studies report a hemispheric lateralization bias for oscillatory responses to speech at these early ages (Peña et al, 2010; Telkemeyer et al., 2011). These results are not surprising, since it is likely that differential hemispheric responses to different aspects of the linguistic signal interact with the acquisition of linguistic competence (Telkemeyer et al., 2011) and lateralization for different aspects of linguistic processing has been consistently shown to increase with age (Holland et al., 2001; Kadis et al., 2011; Ressel, Wilke, Lutzenberger, & Krägeloh-Mann, 2008; Spironelli & Angrilli, 2009; Szaflarski, Holland, Schmithorst, & Byars, 2006; cf. Papanicolaou et al. 2006). Finally, both studies analysed oscillatory activity in terms of amplitude, but no study to our knowledge has examined coherence to natural speech in infants. Indeed, analysing coherence in small infants would without any doubt enrich the literature on the phenomenon, but adults' and infants' oscillatory responses to speech might be too different to compare. Crucially, coherence in adults has been correlated positively with intelligibility, such that coherence in low-frequency bands has been shown to be higher for intelligible signals as opposed to unintelligible signals (Bourguignon et al., 2013; Gross et al., 2013; Molinaro & Lizarazu, 2018; Peelle et al., 2013). Therefore, while oscillatory responses in babies are most likely due to pure analysis of (a familiar) sound, the coherence phenomenon in adulthood seems to be affected by higher order processes such as speech comprehension.

Analysing brain-to-speech coherence in young children who already understand speech might bring more relevant results for the characterisation of its development. Nevertheless, only one study in the field of developmental reading disorders has tested coherence to natural speech in children (Molinaro et al., 2016). In this study, the authors compared the oscillatory response to natural speech of dyslexic and control children and adults (four groups) and, relevant to the current study, found that both the control adults and children (children's mean age: 11.6 years; adults mean age: 32.5 years) showed peaks of coherence at the delta (0.5-1 Hz) and the theta (5.8-6.3 Hz) bands; in both groups and frequency bands, the coherence values were significantly stronger in the right hemisphere sensors (Molinaro et al., 2016). Interestingly, both dyslexic children and adults showed reduced coherence in the delta band in the right sensors, but no difference was found in the left hemisphere. Nevertheless, this study cannot shed light on the early development of the coherence phenomenon, since their young participants were pre-adolescents, and it is well known that speech perception skills are adult-like well before this age. Furthermore, the children could already read, and since coherence has been extensively correlated with reading ability in the literature (Goswami, 2011; J. A. Hämäläinen et al., 2012; Lallier et al., 2017; Lizarazu et al., 2015; Molinaro et al., 2016), this data does not allow exploring causal correlations between the coherence phenomenon and the development of reading skills (issue that will be explored in Experiment 3 of this doctoral thesis). By contrast, an interesting group of age in which to study the development of coherence to speech would be children who can already pay attention and comprehend speech, but whose speech perception abilities are still developing. To our knowledge, such enterprise has never been undertaken before in the literature.

This study

The main aim of this study was to examine the development of the brain-to-speech coherence phenomenon at low-frequency bands during early childhood. To this goal, we recruited a group of four-to-five year old children and followed them up until they were six-to-seven years old. We used EEG to measure their oscillatory responses to natural speech at three different testing times coinciding with the end of the corresponding school year (T1: 4-5 years old; T2: 5-6 years old; T3: 6-7 years old). We chose to start testing the children during their fifth year of life because of several reasons. First, attention skills of children younger than four years are still too immature, which typically leads to excessive movement and discomfort during neurophysiological recordings. Second, according to the American Speech-Language-Hearing Association (ASHA; www.asha.org), in the fifth year of life children develop adult-like grammar and reach an important communicative milestone: the ability to understand most of what they hear and pay attention to short stories. Therefore, before this age we would not have been able to establish clear links between our evidence and the evidence coming from adults and older children, since our intention was to test coherence to *intelligible* speech. Finally, testing the children before and after formal reading acquisition would also allow us assessing the relation between brain-to-speech coherence and literacy skills (Experiment 3).

Hypotheses

Since this was the first study analysing brain-to-speech coherence longitudinally in children, our predictions were based on adult studies analysing coherence measures, and on studies examining the development of speech perception during infanthood and childhood from other fields and/or using different techniques and analyses.

First of all, if the coherence phenomenon is related to intelligibility (Gross et al., 2013; Molinaro & Lizarazu, 2018; Peelle et al., 2013), and given that during their fifth year of life children are able to *fully* understand speech (with their obvious lexical limitations), we expected coherence to speech to be present since the first testing time (T1) and along the subsequent testing times (T2 and T3). Regarding the localization of the effect across the scalp, significant coherence values were expected in temporal and posterior sites based on the sensor level results of MEG-studies performed in adults (Bourguignon et al., 2013; Gross et al., 2013; Molinaro et al., 2016). Finally, based on evidence outside of the language field, we expected coherence values to increase significantly with age (Shahin, Trainor, Roberts, Backer, & Miller, 2010). Shahin et al. (2010) tested oscillatory responses in children and adults (age range from four to 25 years old) and found that phase-locking values to musical tones at different frequency bands (theta, alpha, beta and gamma) correlated positively with age. Nevertheless, due to the lack of previous evidence and the partially exploratory nature of the study, we considered the possibility that the (linear) increase in coherence would not happen evenly across the scalp, i.e. that the distribution of the electrodes showing significant coherence to speech would change along the testing times to acquire a more adult-like shape (i.e. posterior-temporal sites of the scalp) by our final testing time, based on MEG studies showing that in adults coherence to auditory signals is predominantly localised in the auditory cortices (Gross et al., 2013; J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Molinaro et al., 2016).

Lastly, the mixed nature of previous evidence in infants and children measuring the development of language lateralization (Brown et al., 2005; Gaillard et al., 2003; Holland et al., 2001; Papanicolaou et al., 2006) did not allow us having a clear prediction on hemispheric differences for coherence values. Nevertheless, we considered the possibility that hemispheric differences in coherence would change with age and possibly attain an adult-like right-hemispheric bias for speech slow temporal components (i.e. delta and theta bands) by the last of our testing times (T3).

4.1.2. Materials and methods

4.1.2.1. Participants

Thirty-two children (age *M* = 5.11 years; *SD* = .29; 16 males) of the initial battery of 42 children who participated in the study in T1 completed this EEG task. The rest of the children (10) did not complete the task because of discomfort with the EEG cap. Twenty-three and nine children were categorised as Basque or Spanish dominant, respectively. Five of the children were left-handers.

At T2, 34 out of the total sample of 38 children (age *M* = 5.84 years; *SD* = .33; 17 males) that came back for testing at T2 did the task. Twenty-four of these children were Basque dominant and 10 Spanish dominant. Four children were left-handers.

Finally, the 33 children that came back to complete the battery at T3 finished the task (age *M* = 6.98 years; *SD* = .32; 17 males). Twenty-two and 11 children were characterised as Basque or Spanish dominant, respectively. Four children were left-handers.

4.1.2.2. Stimuli and procedure

Children were instructed to fixate their gaze in a static child-friendly image that appeared in the centre of the CTR screen while listening attentively through loudspeakers to Basque natural speech recorded by a native female speaker. Stimuli were delivered via loudspeakers through *Psychopy* (Peirce, 2008) at a 80 dB SPL. For the recording of the text, the speaker was asked to read at a normal pace and not to over-emphasise prosody (i.e. avoid infant directed speech). Pronunciation errors and silences of more than one second were removed from the recordings. The children listened to a different unknown story over the three testing times to avoid attentional disturbances due to familiarity with the story. The recordings were six minutes long and were segmented in one minute fragments. After each of the six fragments, participants were asked a simple yes/no comprehension question (e.g. *Did the child eat the cake in the end?*) to ensure that they understood the story and were paying attention. Before starting the recording, children were told that they would be required to answer some questions, and hence should pay attention to the speech. These recesses were also used to allow the children to rest and move before resuming the experiment.

4.1.2.3. Data analysis

4.1.2.3.1. Data pre-processing

The EEG data were pre-processed and analysed in Matlab 2014b (Mathworks, Natick, MA). After inspection of the raw data we decided to discard directly the data of four participants at T1 and of three participants at T2 due to excessive movement during recording or to reduced number of trials. Unfortunately, the data of six of the children at T3 was not correctly recorded due to a technical problem and hence could not be used for further analysis. Consequently, the data of 28 (T1), 31 (T2), and 27 (T3) children was used in the pre-processing stage. In each individual case, we pooled other channels with excessive noise from the signal of at least three surrounding electrodes. Data were then bandpass-filtered at a range from 0.1 to 40 Hz with a 4 bandpass filter order. The upper threshold was applied at 40 Hz, since no effects were expected at frequencies above that threshold (Bourguignon et al., 2013; Gross et al., 2013; Park et al., 2015). Further inspection of the data indicated the general presence of excessive noise in mastoid channels due to movements. Accordingly, we excluded electrodes A1 and A2 from further analysis, and re-referenced the data offline to electrode Cz. Next, we applied the whole's participant recording a fast Independent Component Analysis (ICA). The audio signal was then added as an independent channel to the EEG configuration and filtered with the same parameters as the EEG signal. We applied a Hilbert transform to obtain the broadband amplitude envelope of the audio signals (Drullman et al., 1994). The pre-processed signals (the audio stimuli and the EEG data) were segmented into 2.048 ms-long epochs with 1.024 ms epoch overlap (Bortel & Sovka, 2007; Bourguignon et al., 2013; Molinaro et al., 2016). This epoch length leads to a frequency resolution of 0.5 Hz (inverse of the epoch duration), and is typical in coherence analyses (Bourguignon et al., 2011; Semmler & Nordstrom, 1999). Epochs with amplitude that deviated more than 3 z-scores from the amplitude mean of the specific channel over all time and trials were discarded. We did not further analyse datasets for which more than 30% of the data was rejected due to excessive movement. This affected two children at T1, two children at T2 and one child at T3. Therefore, the data of 26, 29 and 26 participants was kept for T1, T2 and T3, respectively. For these data sets, an average percentage of 89.2% (*SD* = 11.03), 92.03 (*SD* = 2.99) and 94.13 (*SD* = 3.82) of epochs was kept for the three testing times, respectively, and submitted to the coherence analysis.

4.1.2.3.2. Coherence to natural speech

See section 2.2.4 of Chapter 2 for a description of the coherence measure and its calculation.

Statistical analysis

Coherence between the artifact-free EEG data and the envelope of the signal was calculated in the 0.1-40 Hz frequency range, which yielded a coherence value for each possible combination of EEG channels, frequencies and subjects. Based on previous studies in adults showing significant coherence between the speech and the brain signals in the 0.5 Hz (Bourguignon et al., 2013; Clumeck et al., 2014) and 4–8 Hz (Ding & Simon, 2012b; Peelle et al., 2013) frequency ranges, we focused our analysis in these bands (although coherence was explored in the whole frequency range, i.e. up to 40 Hz).

As we did not have a baseline condition to compare with our real speech signal (given the short age of our participants), we artificially created a surrogated (flipped) signal and assessed statistical significance at the level of the group with a non-parametric permutation test. First, group-level coherence maps for the genuine speech and the surrogated conditions were computed at the frequencies of interest. The difference maps at the group level were calculated by subtracting the *f*-transformed surrogated coherence maps from the genuine coherence maps for each frequency of interest. For the calculation of a significance threshold for the difference map, we computed the sample distribution of the maximum absolute value of the difference map from a subset of 1000 permutations. The coherence thresholds (at $p \leq .05$, corrected for multiple comparisons) were evaluated as the .95 percentile of the corresponding cumulative function (Nichols & Holmes, 2001). The local coherence maxima that surpassed the threshold were interpreted as indicative of electrodes showing group-level statistically significant coupling with the natural speech sound.

4.1.2.3.3. Longitudinal trajectory of coherence to natural speech

Only channels that showed significant coherence to speech as compared to the surrogated speech signals at any frequency band in any of the testing phases were considered for the longitudinal analysis. In principle, since one of our main interests was to test the lateralization of coherence in children, we considered the possibility of averaging coherence values in the electrodes of the left and the right hemisphere. Nevertheless, the longitudinal trajectory of the separate electrodes was examined visually to detect differences among them. This was done in order to avoid obscuring intra-hemispheric differences by averaging. According to this, when the data suggested that the electrodes within the same hemisphere behaved differently along time, coherence values were not averaged per hemisphere, i.e. they were entered separately in the analysis. Note that, in case of individual introduction of the electrodes, hemispheric information would already be coded implicitly in the Electrode factor, and in order to avoid losing degrees of freedom for parameter estimation, the Hemisphere factor was not entered in the model. In other words, we considered entering either the Electrode or the Hemisphere factor, but not both.

With the aim of evaluating statistically the (linear) progression of coherence in the electrodes of interest across the years, we fitted a mixed effects model with the coherence value in the electrodes of interest as dependent variable. See section 3.2.3.2 (*Statistical analysis, Linear mixed models*) in Chapter 3 for details on the procedure followed for model construction and comparison.

We considered two different fixed effects structures that yielded two different models: an initial hypothesis-driven model that included the factors Time (1, 2 and 3), Electrode/Hemisphere (electrodes entered individually or averaged per hemisphere depending on the results of the coherence analysis) and their interaction (Time * Electrode/Hemisphere), and a second model that did not include the interaction (i.e. only Time and Electrode/Hemisphere factors).

Concerning the construction of the random effects, two by-subject slopes for the effect of Time and Electrode/Hemisphere were entered to control for within-subject variability and measures' interdependency. Further random intercept and slopes were entered following the maximal model procedure (Barr et al., 2013).

4.1.3. Results

4.1.3.1. Behavioural responses to the story

At T1, children answered correctly to a mean of 4.3 out of six questions (71%; *SD* = 1.6). The mean accuracy increased to 5.1 (85%; *SD* = 1.2) at T2, and to 5.8 (97%; *SD* = 1.1) at T3. Descriptively, these responses suggested that the speech was intelligible for the children, and that they were paying attention.

4.1.3.2. Coherence to Natural speech

Group-level brain-speech coherence between 0 and 20 Hz can be seen in Figure 4.1.1.a. As shown in this figure, an interesting peak in brain-coherence to speech was detectable only in the delta band (0.5 Hz). Nevertheless, we further analysed the statistical significance of coherence in our second frequency range of interest in the theta band (4-8 Hz).

Coherence at T1

At the group level, the only channel that showed significant coherent activity to speech (as compared to the surrogated signal) was P7. This electrode's signal was coherent with the audio signal at 0.5 Hz (low delta band; see upper panel of Figure 4.1.1.a and left plot of Figure 4.1.1.b). No significant coherence was found in the theta band in any electrode.

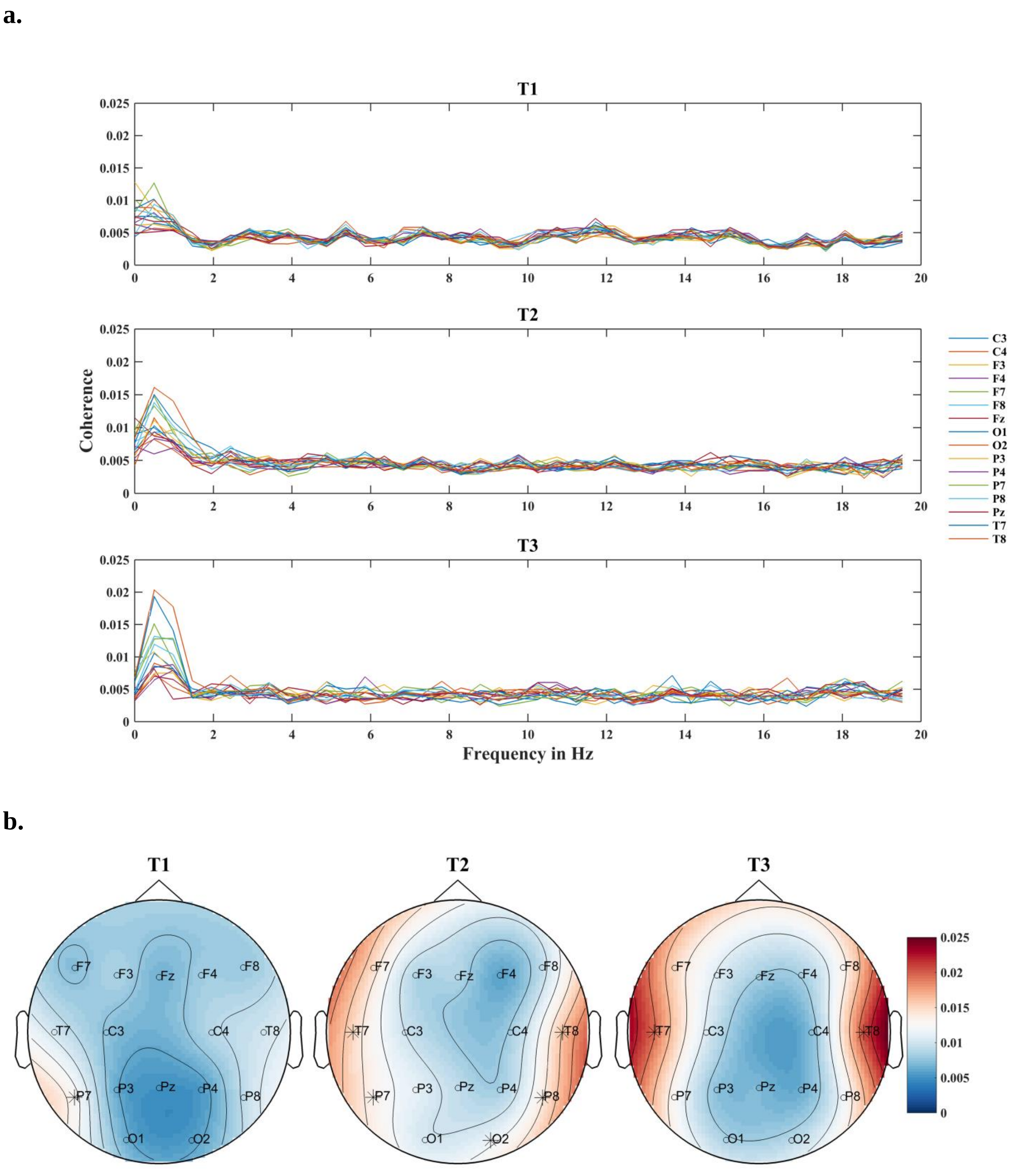

Figure 4.1.1. Developmental trajectory of coherence across the testing times. a) shows mean group coherence between 0 and 20 Hz across the electrodes in T1 (upper panel), T2 (middle panel) and T3 (bottom panel). The coloured lines represent the different electrodes. b) depicts coherence maps at the 0.5 Hz frequency band across the testing times. Electrodes that showed significant coherence to speech are marked with an asterisk (*).

Coherence at T2

Again, we found significant mean group coherence to speech only in the 0.5 Hz frequency (and not in the 4-8 Hz range). Electrodes showing coherent activity were distributed along posterior right (T8, P8, O2) and posterior left (T7, P7) electrodes in the scalp (see middle panel of Figure 4.1.1.a and central plot of Figure 4.1.1.b).

Coherence at T3

As in T1 and T2, we found significant coherence to speech only at the 0.5 Hz band. This time, coherent activity was localised in bilateral temporal electrodes (T7 and T8; see bottom panel of Figure 4.1.1.a and right plot of Figure 4.1.1.b).

4.1.3.3. Longitudinal trajectory of coherence to natural speech

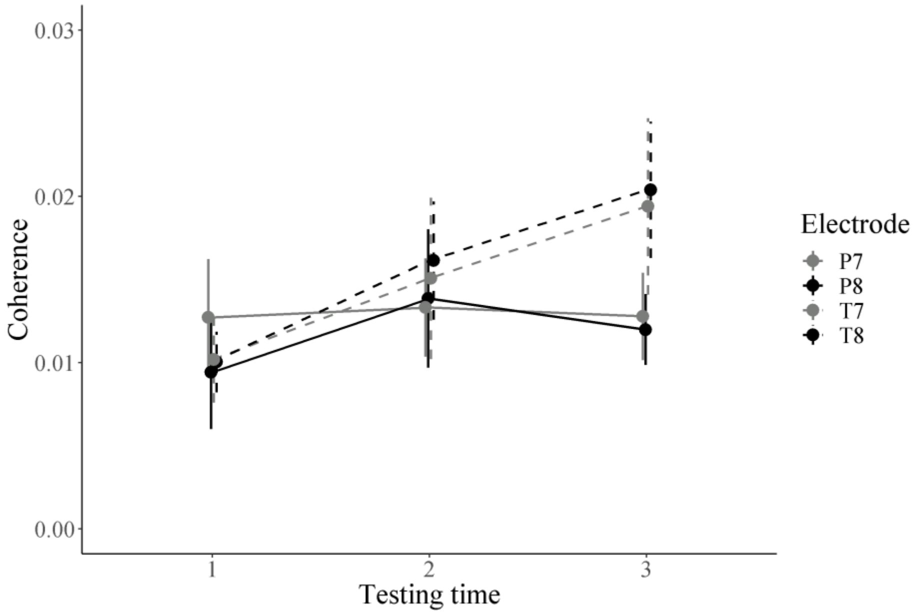

Figure 4.1.2. Development of coherence at 0.5 Hz in the electrodes of interest across the testing times. Vertical bars represent the standard error of the mean. Parietal electrodes are represented with solid lines and temporal electrodes, with dashed lines. Hemisphere is coded in the lines' colour (black: right; grey: left).

Based on the results of the coherence analysis, our only frequency band of interest was the 0.5 Hz band. The electrodes considered for further analysis were T7, P7, T8, P8 and O2. Since significant coherence to natural speech has been shown mostly in temporal-parietal sensors with MEG (Bourguignon et al., 2013; Gross et al., 2013; Molinaro et al., 2016; Peelle et al., 2013; Vander Ghinst et al., 2016), we decided to reduce our array of electrodes to T7, P7, T8 and P8 (electrodes of interest, from now on). Visual inspection of the longitudinal trajectory of the electrodes (see Figure 4.1.2) suggested that the trajectory of coherence values was different between intra-hemispheric pairs (T7 vs. P7, T8 vs. P8).

To avoid obscuring intra-hemispheric differences by averaging activity within the hemispheres, we introduced the electrodes separately in our analysis (see Table 4.1.1 for descriptive statistics at the level of the group in the electrodes of interest).

Table 4.1.1. Mean group-level coherence values (and standard deviation) at 0.5 Hz in the electrodes of interest. Electrodes that showed significant coherence are marked with an asterisk (*).

	Electrode											
	T7			**P7**			**T8**			**P8**		
TT	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**
M	.011	.015*	.019*	.013*	.013*	.013	.010	.016*	.020*	.009	.014*	.012
SD	.013	.026	.027	.018	.016	.013	.009	.019	.021	.017	.022	.011

TT = testing time

Model specification

The analysis of variance comparing the models with and without the interaction between our factors Time and Electrode indicated that the model that included the Time * Electrode interaction had a lower AIC (interaction model: -1818.3; no interaction model: -1821.5) and a larger log likelihood (interaction model: 943.13; no interaction model: 938.74), although the chi-square test testing the statistical difference between the models did not reach significance (χ^2 (6) = 8.79; *p* = .19). Despite the latter, and supported by our hypothesis that coherence values would change across the scalp in the different testing times, we chose the model with the interaction as the best fit of our data.

The final model included hence the fixed effects of Time (T1, T2 and T3), Electrode (T7, P7, T8 and P8) and their interaction, and the random by-subject slopes for Time and Electrode initially entered in the model plus a random by-subject intercept. The total number of different subjects included in the analysis amounted to 36, and the number of observations to 324.

Model results

The summary of the model's random effects can be seen in Table 4.1.2.a. The estimates of the model or least square means (LSMs, thereafter) together with their *SE* and upper and lower confidence levels (CL) are presented in Table 4.1.2.b. Inspection of the estimates suggested that the only electrodes whose coherence values increased linearly along time were T7 and T8. Regarding the difference in coherence among the electrodes within each testing time, the only difference in the estimates that seemed relevant was within T3 and between parietal and temporal electrodes (P7 LSM: .12; P8 LSM: .11, T7 LSM: .18; T8 LSM: .20).

Table 4.1.2. Mixed effects model's output with the coherence value at 0.5 Hz as dependent variable and the Time, Electrode and Time * Electrode factors as fixed effects, and with by-subject slopes for Time and Electrode and by-subject intercept as random effects

a. Output of the random effects structure. Reference levels are electrode P7 for the Electrode factor and T1 for the Time factor

Random effect	***SD***
Intercept	.007
Electrode P8	.005
Electrode T7	.005
Electrode T8	.005
T2	.012
T3	.006
Residual	.010

b. Fixed effects estimates (LSM), standard errors and confidence levels (.95) for the different levels of the factors Time and Electrode

Time	**Electrode**	**LSM**	***SE***	**Lower CL**	**Upper CL**
1	P7	.012	.003	.007	.017
2		.014	.003	.007	.021
3		.012	.003	.006	.018
1	P8	.008	.003	.003	.014
2		.014	.004	.006	.022
3		.011	.003	.005	.017
1	T7	.009	.003	.003	.015
2		.016	.004	.007	.024
3		.018	.004	.011	.025
1	T8	.009	.002	.004	.014
2		.016	.004	.009	.024
3		.020	.003	.014	.026

We moved on to test statistically the significance of these effects by computing the pairwise contrasts with Tukey correction (from *R* package *lsmeans*). For parsimony reasons, only significant results will be discussed in text (complete results can be seen in Table 4.1.3). When the effect of Time on the different Electrodes was tested (see Table 4.1.3.a), the only significant contrast was the one comparing T1 and T3 in Electrodes T7 (contrast estimate = -.010, t = -2.82; p = .01) and T8 (contrast estimate = -.010; t = -3.13; p = .006). Since the difference was coded as T1 minus T3, the negative estimate meant that there was a linear increase in coherence for these electrodes along time, while coherence did not increase or decrease (linearly) in electrodes P7 or P8 as the children's age increased. Regarding the contrasts comparing the different electrodes within the testing times (see Table 4.1.3.b), only the contrast between electrodes P8 and T8 within T3 was significant (contrast estimate = -.008, t = -2.72; p = .04).

Table 4.1.3. Tukey-corrected least square means contrasts

a. Effect of Time on Electrode

Contrast (Time)	LSM	*SE*	*t*	*p*
Electrode P7				
1-2	-.002	.004	-.49	.88
1-3	-.0001	.003	-.04	1.00
2-3	.001	.003	.48	.87
Electrode P8				
1-2	-.006	.004	-1.53	.28
1-3	-.003	.003	-.80	.70
2-3	.003	.003	.92	.63
Electrode T7				
1-2	-.007	.004	-1.80	.18
1-3	-.01	.003	-2.82	.01*
2-3	.003	.003	-.78	.72
Electrode T8				
1-2	-.007	.004	-1.92	.14
1-3	-.01	.003	-3.13	.005*
2-3	-.003	.003	-.92	.63

b. Effect of Electrode on Time

Contrast (Electrode)	LSM	*SE*	*t*	*p*
Time 1				
P7-P8	.004	.003	1.09	.69
P7-T7	.003	.003	.97	.77
P7-T8	.003	.003	.86	.82
P8-T7	-.0004	.003	-.13	1.00
P8-T8	-.0008	.003	-.25	.99
T7-T8	-.0003	.003	-.1	1.00
Time 2				

P7-P8	-.0004	.003	-.14	1.00
P7-T7	-.002	.003	-.63	.92
P7-T8	-.003	.003	-.86	.83
P8-T7	-.002	.003	-.49	.96
P8-T8	-.002	.003	-.75	.88
T7-T8	-.0007	.003	-.23	1.00
Time 3				
P7-P8	.001	.003	.32	.99
P7-T7	-.006	.003	-1.95	.21
P7-T8	-.007	.003	-2.30	.10
P8-T7	-.007	.003	-2.25	.12
P8-T8	-.008	.003	-2.72	.04*
T7-T8	-.001	.003	-.35	.99

Follow-up analysis: Assessment of hemispheric differences

Based on inter-hemispheric differences found previously in the literature in coherence values in adults (Bourguignon et al., 2013; Gross et al., 2013; Molinaro et al., 2016), we performed a follow-up analysis to discard definitely the existence of inter-hemispheric differences in our sample and with our stimuli. Multiple paired Mann-Whitney *t*-tests were performed comparing the pairs of electrodes from the left and the right hemisphere (i.e. P7 vs. P8; T7 vs. T8) separately for the different testing times. No difference between any of the pairs of electrodes was found for any testing time. The results of these tests can be seen in Table 4.1.4.

Table 4.1.4. Results of the multiple paired Mann-Whitney tests comparing coherence values in the inter-hemispheric pairs of electrodes across testing times

Testing time	Electrode pair	U	*p*
1	P7 vs. P8	393	.32
	T7 vs. T8	290	.39
2	P7 vs. P8	451	.64
	T7 vs. T8	334	.18
3	P7 vs. P8	333	.93
	T7 vs. T8	293	.42

4.1.4. Discussion

This study examined the development of brain-to-speech coherence in young children. As expected, coherence to speech was found already when children were four-to-five years old (T1), and continued developing across the subsequent testing times (T2 and T3). Crucially, we found coherence to speech only in the 0.5 Hz band, replicating studies performed in adults with natural speech (Bourguignon et al., 2013; Gross et al., 2013; Molinaro et al., 2016). By contrast, we did not find any significant effect in one of our frequency bands of interest: the 4-8 Hz band (Gross et al., 2013; Peelle et al., 2013). We believe that the absence of the effect in the theta band could be due to several reasons, among which we could highlight the temporal particularities of the language we tested or the language acquisition stage of our participants. Regarding the first possible reason, it is important to remind that phrasal prosody, which is coded in the delta band (Ghitza & Greenberg, 2009; Goswami, 2011), is different in Basque as compared to commonly tested languages such as Spanish (Molinaro et al., 2016), English (Gross et al., 2013) or French (Bourguignon et al., 2013). As mentioned in section 2.1.2 of Chapter 2, the phrasal prosody of Basque is characterised by a predominant iambic metric derived from its complement-head word order (Molnar, Gervain, et al., 2014), as opposed to languages such as English, Spanish or French, whose metrics at the phrasal level are predominantly trochaic. One of the possibilities is that these differences in phrasal prosody (in the delta frequency range) originate differences in the theta range, given the hypothesis that activity in these frequency bands is nested, such that activity in the delta band would modulate activity in the theta band (Canolty et al., 2006; Gross et al., 2013; Lakatos et al., 2005; Morillon et al., 2012). In this sense, the absence of theta coherent activity could be due to the temporal characteristics of the language we tested. Indeed, although previous research studying entrainment has focused on generic timescales across languages, there is evidence that the maximum coherent activity in adults is found in frequency bands corresponding to the prominent statistical regularities of the tested linguistic material (Keitel et al., 2018). Moreover, differential coherence patterns found in different languages, specifically in the field of dyslexia, also suggest that the prominence of coherence in the delta and/or the theta band could be language specific (Lallier et al., 2017; Lizarazu et al., 2015). Concerning the second possible explanation, children with immature linguistic and reading skills are also generally more sensitive to slow as opposed to fast information in the speech signal

(Anthony & Francis, 2005; Ziegler & Goswami, 2005), which could also explain why coherence was only found in the lowest frequencies. Only cross-linguistic research will be able to disentangle these accounts.

For the brain-to-speech coherence in the delta band, we report interesting effects regarding the developmental trajectory of coherence and its scalp distribution across the testing times. First, considering the testing times separately, we observed developmental changes regarding the localization of significant brain-to-speech coherence. The longitudinal trajectory of the coherence maps was characterised by the presence of a single significant left posterior electrode at T1 which evolved to a distributed bilateral posterior-temporal network in T2 and reached a more focal bilateral temporal configuration in T3. The developmental trajectory from T2 to T3 is not surprising, given that language networks have been consistently shown to evolve from diffuse to focal (Brown et al., 2005; Holland et al., 2001; Ressel et al., 2008). By contrast, the finding that coherence in the delta band in T1 was absent in the right hemisphere is to a level puzzling, since based on the literature in infants, we expected coherence at the delta band -which codes in principle for the slow-rhythmic (prosodic) aspects of speech- to appear in the right hemisphere already in early childhood (Homae et al., 2006; Perani et al., 2011; Telkemeyer et al., 2009, 2011). Nevertheless, a different study from our lab has also found left-lateralised coherence to speech in five-year olds (Pérez-Navarro, Molinaro, & Lallier, 2018, poster communication), which supports the idea that our own result is not spurious. Moreover, Molinaro et al. (2016) found significant delta coherence to speech in children and adults not only in the right auditory cortex, but also in the left inferior frontal gyrus. It is also important to point out that the studies testing young infants and children found right lateralization for speech slow information when comparing non-linguistic sounds modulated at different (slow vs. fast) rates (Telkemeyer et al., 2009, 2011) or when comparing natural speech with speech deprived of pitch (Homae et al., 2006; Perani et al., 2011). Evidently, it is difficult to compare our results with these, since no manipulation was applied to our natural speech stimuli. Furthermore, neuroimaging longitudinal studies have shown that lateralization patterns for language tasks change even when children are older (Holland et al. 2007), and there is no reason to discard that coherence to speech changes over the course of development until it acquires its typical mature configuration. Another interesting explanation for the left lateralization of the brain-to-speech coherence in children emerges when looking at the literature in adults, and specifically to the studies that found a correlation between coherence measures and intelligibility (Gross et al., 2013; Molinaro & Lizarazu, 2018; Peelle et al., 2013). These studies suggest indeed that, further beyond encoding *only* for prosody or for syllabic information, lower frequency bands, and specially the delta band (Molinaro & Lizarazu, 2018) could also encode for intelligibility cues. From the developmental perspective, the encoding of these cues could be initially left-lateralised because of its importance for linguistic processing when speech perception is in place, but still not fully established (as is the case of our children in T1). Hence, left lateralization of the effect could be more related to comprehension, or listening effort, than to prosodic processing itself. Descriptively, this could be supported by the accuracy in the response to the comprehension questions, which was low at T1 (71%) as compared to T2 and T3 (85% and 97%, respectively).

In any case, the logical progression of the coherence phenomenon and specially the linear increase across phases in temporal electrodes suggests that our results are not due to global developmental changes in electrophysiological activity (Benninger, Matthis, & Scheffner, 1984; Thatcher, 1992), but specific to our stimulus. Indeed, the only statistically significant linear increase in coherence across the testing times was found between T1 and T3 and in bilateral temporal electrodes (T7 and T8). This developmental change goes in line with previous evidence that found an increase in phase-locking value to musical stimuli with age (Shahin et al., 2010) and also with evidence showing linear changes in EEG band power in several frequencies (delta, theta, alpha and beta) from childhood into adulthood during rest and also during task performance (Benninger et al., 1984; Gasser, Verleger, Bächer, & Sroka, 1988). Due to the auditory nature of our stimulus, the fact that coherence increased linearly only in temporal sites (i.e. adult-like topography at the sensor level; Bourguignon et al., 2013; Gross et al., 2013; Molinaro et al., 2016) supports the idea that the effect was related to the interaction between age and the linguistic stimulus, and not merely to electrophysiological changes related with age.

No significant inter-hemispheric differences in coherence to speech in temporal sites of the scalp were found at any testing time. This suggests that the right auditory cortex bias found for brain-to-speech coherence in adults has not yet been attained at around seven years old. Molinaro et al. (2016) found adult-like coherence in terms of lateralization in pre-adolescent children (approx.11 years old), fact that, together with our evidence, suggests that coherence could acquire the adult right-hemispheric bias during late childhood. Nevertheless, multiple factors could be at the base of this lateralization shift with age. First, it has been proposed that from the developmental perspective, connections in the young brain would be best described as inter-hemispheric (with communication occurring predominantly between left and right superior temporal regions), as opposed to the adult brain, where left intra-hemispheric connections are prevalent for language processing (Friederici, Brauer, & Lohmann, 2011). Nevertheless, it is important to highlight that the evidence on the development of hemispheric lateralization for language is mixed. On the one hand, positive results on a bilateral-to-lateralised trajectory of activation from childhood into adulthood has been reported using neurophysiological (Kadis et al., 2011; Pihko et al., 2005; Ressel et al., 2008; Spironelli & Angrilli, 2009) and hemodynamic (Brown et al., 2005; Holland et al., 2001; Szaflarski et al., 2006) measures. On the other hand, several studies failed to find lateralization differences across age groups (Gaillard et al., 2003; Papanicolaou et al., 2006; Wood et al., 2004). Finally, we cannot discard that the psycholinguistic profile of our participants had some influence in the bilateral response pattern we report. Our participants were Basque-Spanish bilinguals from birth or learnt both languages before their third year of life, and early bilinguals have been shown to process both native languages in a more bilateral manner, as opposed to late bilinguals and monolinguals, for which native language processing is normally left-lateralised (Hull & Vaid, 2007). In conclusion, our and previous results seem to be very influenced by the task, the age and the neuropsychological profile of the participants tested, and hence taking into account these variables seems necessary to describe, predict and explain the astonishing complexity of language development during childhood.

Lastly, even though the coherence values resulted significant in temporo-parietal sites of the scalp after correction for multiple comparisons was applied, the coherence values of the children were generally low even in our last testing time (range from .0004 to .12). Nevertheless, in the field of physiology coherence values below .10 have been consistently reported across studies examining the relation between brain and electromyographic activity, among others (Conway et al., 1995; Gross et al., 2005; Pohja, Salenius, & Hari, 2005; Pollok, Gross, Dirks, Timmermann, & Schnitzler, 2004; Salenius, Portin, Kajola, Salmelin, & Hari, 1997).

Conclusions of Experiment 1

This work corroborates that the brain-to-speech coherence phenomenon at low-frequency bands occurs already in childhood, which supports a relevant biological meaning of this phenomenon for the establishment of adult-like speech perception abilities. Moreover, this is the first study providing data on its longitudinal trajectory. Coherence to speech was localised in the left hemisphere when children were four-to-five years old, distributed along bilateral posterior-temporal sites of the scalp when they were five-to-six, and focused on bilateral temporal electrodes one year later. Future studies might reveal the putative functional correlates of such topographical changes and examine in depth the role of inter-hemispheric differences for speech processing.

4.2. Experiment 2: The development of coherent oscillatory activity in response to non-linguistic auditory signals modulated at speech-relevant rates

The natural speech signal is an ecological stimulus to test brain oscillatory activity in response to acoustic stimuli, but since it contains verbal information, it is not possible (at least with the current state of the literature) to separate *pure* acoustic (rhythmic) processing from higher linguistic processes (e.g. syntactic, semantic, etc.). An alternative to test purely rhythmic processes is to deprive the signal of verbal information using non-linguistic signals (e.g. white noises) and modulating their amplitude at the different rhythms characteristic of the speech signal. Accordingly, this second experiment was aimed at complementing our results with the natural speech signal (Experiment 1) and further test oscillatory dynamics in response to the rhythms of speech in absence of linguistic information.

4.2.1. Introduction

The speech signal is a complex sound that contains amplitude modulations (AMs) at different temporal rates. These fluctuations in amplitude generate the speech *amplitude envelope* (AE), which contains information at rates ranging from 2 to 50 Hz (Rosen, 1992). Crucial information on the speech structural rhythm is contained in the low frequencies of the AE (<8 Hz; Houtgast & Steeneken, 1985), although both low and high-frequencies contribute significantly to speech intelligibility (Drullman et al., 1994; Horst et al., 1999; Shannon et al., 1995). Recent neuroscientific theories suggest that the cerebral hemispheres are specialised in processing information at different temporal scales, such that fluctuations at low frequencies – which would code for changes in amplitude originated by prosody and stress (~500 ms; delta band; <4 Hz) and by syllable chains (~200 ms; theta band: 4-8 Hz)– would be preferentially processed in the right hemisphere, while high frequencies –which would code for phonemic information (~80 ms; ~30 Hz; gamma band)– would be processed in the left hemisphere or bilaterally (Ghitza, 2011; Giraud et al., 2007; Giraud & Poeppel, 2012; Goswami, 2011; Poeppel et al., 2008). Several studies have provided support to this hypothesis. Differential lateralization patterns for the different AMs of speech have been found in adults (J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015) and children (De Vos et al., 2017; Lizarazu et al., 2015; Vanvooren, Poelmans, Hofmann, Ghesquiere, & Wouters, 2014). Regarding the direction of the inter-hemispheric differences, while it has been consistently shown that AMs at low frequencies have a right-hemispheric bias (Boemio et al., 2005; J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Poelmans, Luts, Vandermosten, Ghesquière, et al., 2012), the debate is open regarding fast modulations, for which either a left (Lehongre, Morillon, Giraud, & Ramus, 2013; Lehongre et al., 2011) or a bilateral (Boemio et al., 2005; J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015) hemispheric bias has been reported.

Importantly, synchronised brain activity in response to AM signals at both slow and fast rhythms and to periodic linguistic stimuli (syllables) has been consistently associated with language developmental disorders such as developmental dyslexia (Goswami, 2011; Lallier et al., 2017; Lehongre et al., 2013; Lizarazu et al., 2015; Poelmans, Luts, Vandermosten, Boets, et al., 2012; Power et al., 2013). This evidence suggests that synchronised neural activity to the AMs of speech might be crucial for the development of appropriate speech perception and subsequent phonological abilities, which are in turn essential for reading development (Goswami, 2011, 2018; Goswami et al., 2014; Lallier et al., 2018, 2017). That being the case, research assessing the longitudinal trajectory of coherence to the different AMs of speech in children whose linguistic skills are not yet developed could have incredible value for the early detection and intervention of developmental language disorders, and some pioneer work in this direction has been reported in the literature.

Impressively, a study using NIRS showed that 3-days-old babies already processed non-linguistic acoustic signals differently depending on their modulation rate: while modulations at the phonemic level were preferentially processed bilaterally, modulations at the syllabic/prosodic level showed a clear right lateralization (Telkemeyer et al., 2009). The authors replicated this result with six-month old babies, but were not able to replicate it with three-month olds, who showed left lateralization for both slow and fast modulations (Telkemeyer et al., 2011). Using a similar paradigm, Vanvooren et al. (2014) measured the auditory steady-state responses (ASSRs) of young pre-reading children (five years old) while listening to non-linguistic acoustic signals modulated at the syllable (4 Hz) and at the phoneme rate (20 Hz). The authors found that the ASSR was prominently right-lateralised for the syllabic rate modulations, while no hemispheric differences were detected for the phonemic rate modulations, which led them to conclude that syllabic modulations are preferentially processed in the right hemisphere already from childhood. A later study from the same research group in which they followed the same sample of children until they were nine years old (De Vos et al., 2017) confirmed that ASSRs in response to syllable rate modulations did not show developmental effects, such that they were right-lateralised across testing times.

Unfortunately, these studies did not test any modulation under 4 Hz, and hence no information on the lateralization for prosodic information is available for these age groups. Overall, the (scarce) corpus of infant and child evidence speaks in favour of the idea that the hemispheric specialization for different temporal aspects of the linguistic signal is already present at birth (but see Telkemeyer et al., 2011), and hence provides support to models suggesting that the cerebral hemispheres collaborate in the resolution of the time conundrum presented by the linguistic signal (Boemio et al., 2005; Giraud & Poeppel, 2012; Poeppel, 2003; Poeppel et al., 2008).

Considering together the evidence from infants and adults, one could conclude that, at least in terms of lateralization, different temporal aspects of speech are processed in an *adult-like* manner since birth, and no important changes are predicted during language acquisition in childhood. Nevertheless, this conclusion seems hasty for two main reasons: a methodological one and a developmental one. Regarding the methodological reason, there is a crucial difference between the infants/children and the adults studies: whereas studies in adults have used measures based on brain phase correlation across trials such as inter-trial coherence or phase-locking value (J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Power et al., 2013), studies with babies and children have used either the changes in the infants' hemodynamic response (Telkemeyer et al., 2009, 2011) or EEG power measures (De Vos et al., 2017; Telkemeyer et al., 2009, 2011; Vanvooren et al., 2014). No study has therefore targeted specifically phase coherence measures in infants or young children. Concerning the developmental reason, coherence to the rhythmic modulations of speech at different rates could follow a complex trajectory characterised by the interaction between age and language expertise (Telkemeyer et al., 2011). Supporting this, it has been previously suggested that young children are more sensitive to the slow as opposed to the fast modulations of speech, and that left-biased sensitivity to the phoneme rate should increase with age hand in hand as soon as reading is acquired and develops (Anthony & Francis, 2005; Morais, Alegría, & Content, 1987; Ziegler & Goswami, 2005). In fact, there is evidence that infants are *trained* to be sensitive to prosodic stress since birth (Curtin, 2010; Molnar, Lallier, et al., 2014), while the alphabetic principle, i.e. the awareness that letters represent sounds of the oral language, is taught at least five or six years later in Western societies. Supporting this, a cross-sectional study comparing children (from 8 to 14 years old) and adults (from 17 to 45 years old) found that coherence to sounds modulated at the phonemic rate (30 Hz) increased significantly with age (Lizarazu et al., 2015). Furthermore, although using a power measure, the study by De Vos et al. (2017) found that there was an increase in the ASSRs in response to the 20-Hz AMs when children were seven years old (beginning readers) as compared to when they were five (pre-readers), and that this increase was inversely correlated with reading abilities. These studies suggest that changes in brain synchronization to the different components of the AE are expected as the children grow and acquire new linguistic skills. Nevertheless, to our knowledge no study has yet examined these changes with phase coherence measures.

This study

The main purpose of this longitudinal study was to test the developmental trajectory of brain coherence to relevant slow and fast amplitude modulations (AMs) of the speech envelope. To that aim, we used EEG to test a cohort of children when they were four-to-five (T1), five-to-six (T2) and six-to-seven years old (T3). Importantly, the children started receiving formal reading instruction between T2 and T3, which gave us the opportunity to examine the putative effect of learning to read in the coherence phenomenon (Experiment 3). To test our hypotheses, we measured children’s brain coherence while they listened to white noises whose amplitude was modulated at 2 (delta), 4 (low theta), or 30 (gamma) Hz. These AM rates have been previously used in the literature in adults (Lizarazu et al., 2015) and correspond to the approximate rate of occurrence of phrasal stress, syllables and phonemes, respectively (Ghitza & Greenberg, 2009; Goswami, 2011).

Hypotheses

In spite of the mainly exploratory nature of this work, we hypothesised that children would show significant coherence when listening to the noises modulated at slow rates (i.e. 2 and 4 Hz) already at T1, while coherence would be modest for the 30-Hz AM rate before children knew how to read (T1 and T2), and maybe established after children had been formally trained in the alphabetic principle and in reading (T3). This hypothesis was based on previous results showing that young (pre-reading) children are more sensitive to the slow components of speech, such that sensitivity to linguistic components at fast rates should increase with age and reading experience (Anthony & Francis, 2005; Morais et al., 1987; Ziegler & Goswami, 2005), and on studies showing that synchronised power (De Vos et al., 2017) and phase-coherent (Lizarazu et al., 2015) responses to acoustic signals modulated at high rates increase significantly as children develop.

Concerning hemispheric differences, we expected low-frequency components (2 and 4 Hz) to be right-lateralised already from T1, based on previous literature in children and adults (J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Poelmans, Luts, Vandermosten, Ghesquière, et al., 2012; Vanvooren et al., 2014). We had no clear predictions on the lateralization of coherence for the 30-Hz AM rate, since both left (e.g. Lehongre et al., 2011, 2013) and bilateral (J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Vanvooren et al., 2014) patterns have been reported in the literature. In any case, based on results previously presented in this doctoral thesis in which coherence to Natural speech was evaluated (see Experiment 1), we did not discard the possibility that coherence in our children had not yet acquired the typical adult features, both in terms of presence/absence of coherence to the different AMs and of lateralization.

4.2.2. Materials and methods

4.2.2.1. Participants

Out of the initial battery of 42 children, 33 (age *M* = 5.11 years; *SD* = .31; 15 males) completed the EEG task at T1. The remaining nine children did not complete the task because of discomfort with the EEG cap. Twenty-two children were Basque dominant and 11 Spanish dominant. Four of the children were left-handers.

At T2, 33 out of the total sample of 38 children (age *M* = 5.85 years; *SD* = .33; 17 males) that came back for testing did the task. Twenty-three and ten children were categorised as Basque or Spanish dominant, respectively. Four children were left-handers.

Finally, the 33 children that came back to complete the battery at T3 finished the task (age *M* = 6.98 years; *SD* = .33; 17 males). Twenty-two and 11 children were characterised as Basque or Spanish dominant, respectively. Four children were left-handers.

4.2.2.2. Stimuli and procedure

We used Matlab 2014b (Mathworks, Natick, MA) to create the auditory stimuli. These were generated by modulating the amplitude of white-noise sounds. The frequencies used for the modulation were 2, 4 and 30 Hz with 100% depth. The stimuli sampling frequency was of 44.1 kHz. The duration of all stimuli was of 10 seconds, and they were repeated 20 times through the task (total of 60). Stimuli were presented in a pseudorandomised order, such that two stimuli of the same modulation never appeared consecutively.

During the EEG-recording, children listened to the stimuli while watching a silent cartoon movie in the EEG room. They were instructed to stay as still a possible and avoid speaking and making head movements. Stimuli were delivered via loudspeakers through *Psychopy* (Peirce, 2008) at a 80 dB SPL. Children were allowed to take breaks whenever desired.

4.2.2.3. Data analysis

4.2.2.3.1. Data pre-processing

The EEG data were pre-processed and analysed in Matlab 2014b. Inspection of the raw data suggested that the data of five participants at T1 and of three participants at T2 did not contain enough number of trials for an appropriate analysis or was too contaminated by movement noise. Consequently, the data of 28, 30, and 33 children for T1, T2 and T3, respectively, was used in the pre-processing stage. Due to an unfortunate technical issue during the creation of the stimuli at T1, the AMs of the signals were doubled, and hence the children listened to sounds modulated at 4 Hz, 8 Hz and 60 Hz rates. Therefore, for T1 we only analysed the 4-Hz amplitude modulation (AM). For T2 and T3, pre-processing was performed in the 2-Hz, 4-Hz and 30-Hz AMs, as planned. We pooled channels with excessive noise from the signal of at least three surrounding electrodes for each individual subject. Data were then bandpass-filtered at a range from 0.1 to 40 Hz with a 4 bandpass filter order. Slight head movements generated excessive noise in the mastoid channels, so electrodes A1 and A2 were excluded and data were re-referenced offline to electrode Cz. Next, we applied a fast Independent Component Analysis (ICA) to each participant's recording. The data were then segmented into epochs whose duration was of two modulation cycles with one modulation cycle overlap, which resulted in epochs of different length for the different conditions (2 HZ: 1000 ms; 4 Hz: 500 ms; and 30 Hz: 66 ms). For each frequency, subject and testing time, we discarded epochs that exceeded the amplitude mean of the specific channel over all time and trials of the dataset in 3 or more *z*-scores. Datasets for which more than 30% of the data was rejected across conditions due to excessive movement were not further analysed. Consequently, the data of three (T1), four (T2) and one (T3) participant(s) were excluded. The subsequent coherence analysis was therefore performed on the data of 25, 26 and 32 children at T1, T2 and T3, respectively. The average percentage of artifact-free epochs for the remaining data sets was of 89.13% (*SD* = 7.14; T2) and 95.67% (*SD* = 6.12; T3) for the 2-Hz AM rate, of 87.33% (*SD* = 9.44; T1), 90.06% (*SD* = 6.45; T2) and 93.54% (*SD* = 5.28; T3) for the 4-Hz AM rate, and of 91.32% (*SD* = 6.25; T2) and 94.23% (*SD* = 6.54; T3) for the 30-Hz AM rate. No significant differences were found between the number of epochs kept in each of the conditions across the testing times.

4.2.2.3.2. Coherence

See section 2.2.4 of Chapter 2 for a description of the coherence measure and of its calculation.

Statistical analysis

Coherence between the artifact-free EEG data and the envelope of the audio signal was calculated for the 2-, 4- and 30-Hz AM rates separately. For the calculation of statistical significance at the group level, a non-parametric permutation test (Nichols & Holmes, 2001) was applied comparing the genuine brain signal while listening to the *correct* condition as opposed to random epochs extracted from the remaining conditions (e.g. for the 2-Hz condition, the set of all epochs for the 2-Hz condition was compared to random epochs from the brain signal while listening to the 4- and 30-Hz conditions). Group level coherence maps were calculated for each condition separately (T1: 4 Hz; T2 and T3: 2, 4 and 30 Hz). Note that at T1 the comparison stimuli for the 4-Hz AM were the 8 and 60-Hz AMs. The difference maps at the group level were calculated by subtracting the *f*-transformed random coherence values for each electrode from the genuine coherence values for each frequency of interest. The significance threshold for the difference map was calculated computing the sample distribution of the maximum absolute value of the difference map from a subset of 1000 permutations. The coherence thresholds were set at $p \leq .05$ (corrected for multiple comparisons) and evaluated as the .95 percentile of the corresponding cumulative function (Nichols & Holmes, 2001). The local coherence maxima that surpassed the threshold were interpreted as indicative of electrodes showing group-level statistically significant coupling with the corresponding audio signal.

4.2.2.3.3. Longitudinal trajectory of brain-to-speech coherence

Only AMs for which there was significant coherence to the correct as compared to the random conditions at any testing time were analysed longitudinally. Within each AM, only electrodes that showed significant coherence in any of the testing phases were considered for further analysis. Coherence to amplitude modulated (AM) sounds has been previously shown to stem from the auditory cortices (J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015). Hence, we reduced our electrodes of interest to parietal and temporal sites of the scalp. In order to evaluate statistically the (linear) progression of coherence in the different electrodes in each of the modulations across the years, we fitted a separate mixed effects model for each AM of interest using the *lme4* package available in R (Baayen et al., 2008; R Core Team, 2017). The coherence value in the corresponding AM was set as the dependent variable of the respective models. See section 3.2.3.2 (*Statistical tests, Linear mixed models*) for details on the procedure followed for model construction and comparison.

As for Experiment 1 (see section 4.1.2.3.3), we first visualised the data to spot possible differences between intra-hemispheric electrodes. When plotting suggested that this was the case, the electrodes were not averaged across hemispheres, but entered separately in the model.

We considered two different fixed effects structures that yielded two different models: an initial hypothesis-driven model that included the factors Time (1, 2 and 3), Electrode/Hemisphere and their interaction (Time * Electrode/Hemisphere), and a second model that did not include the interaction (i.e. only Time and Electrode/Hemisphere factors).

Concerning the construction of the random effects, two by-subject slopes for the effect of Time and Electrode/Hemisphere were entered to control for within-subject variability and measures' interdependency. Further random intercept and slopes were entered until a maximal model was reached (Barr et al., 2013).

4.2.3. Results

This section presents the results for the coherence analysis across testing times and AM rates (section 4.2.3.1) and the longitudinal progression of coherence in our electrodes of interest in the different amplitude modulation (AM) rates (section 4.2.3.2).

4.2.3.1. Coherence

Coherence maps across the testing times can be seen in Figure 4.2.1.

4.2.3.1.1. Coherence to the 2-Hz AM

T1

As mentioned above, the data of for the 2-Hz AM was not available at T1.

T2

Significant coherence was found in a distributed network of left (T7, P7, P3 and O1) and right (T8, P8, P4 and O2) posterior-temporal electrodes.

T3

Significant coherence was found again in posterior-temporal electrodes of the scalp in the left (P7, T7, P3) and right (P8, T8, P4) hemispheres.

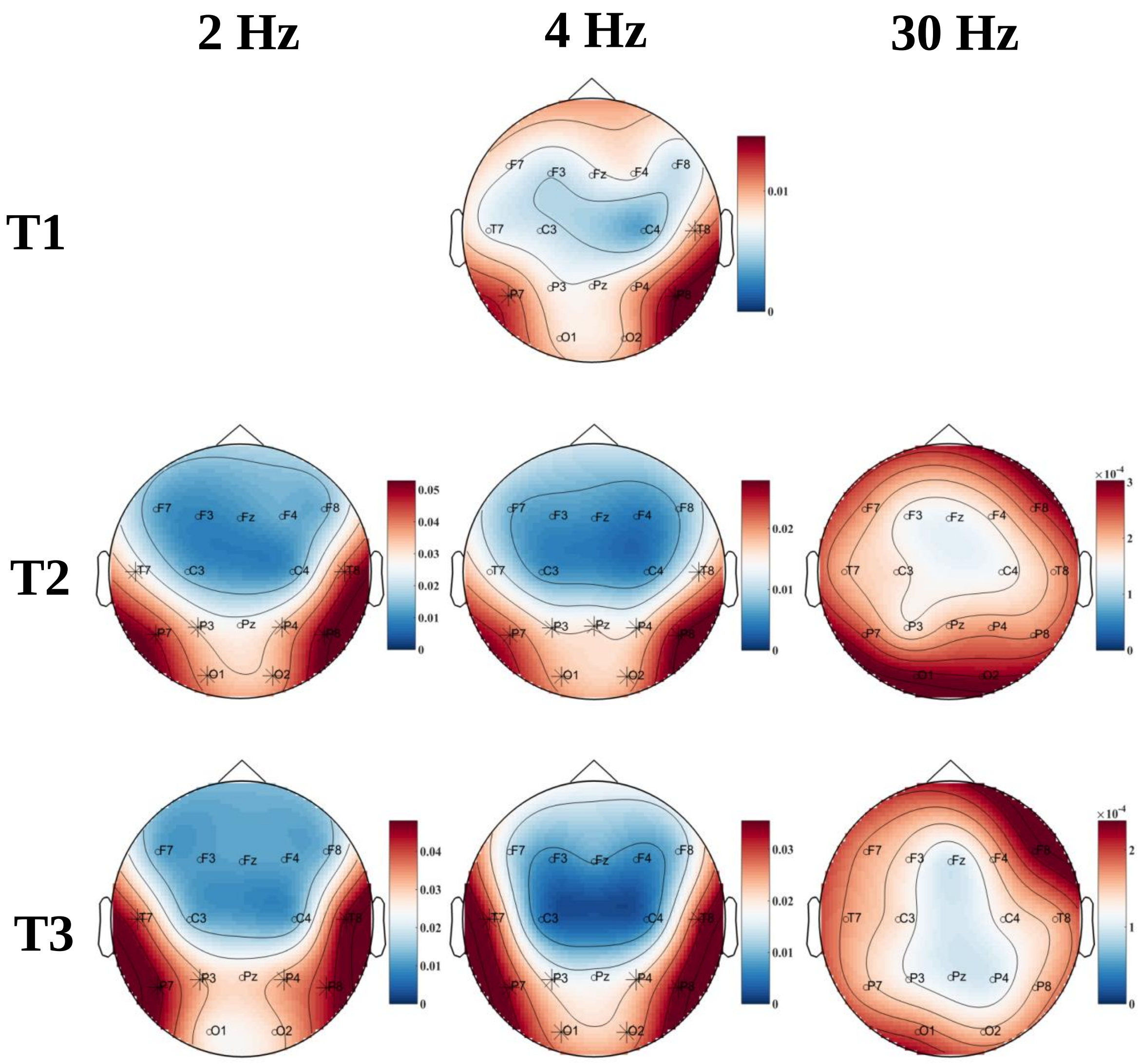

Figure 4.2.1. Group coherence maps across the testing times and AMs. Electrodes that showed significant coherence are marked with an asterisk (*).

4.2.3.1.2. Coherence to the 4-Hz AM

T1

At the group level, electrodes P7 and P8 showed significant coherence when listening to the AM rate at 4 Hz.

T2

Electrodes on which significant coherence was found were again located in bilateral posterior-temporal areas of the scalp (P7, P3, O1, Pz, T8, P8, P4 and O2).

T3

Similarly, electrodes with significant coherence were located in bilateral posterior-temporal electrodes (T7, P7, P3, O1, T8, P8, P4 and O2).

4.2.3.1.3. Coherence to the 30-Hz AM

No significant coherence was found in any of the electrodes for the 30-Hz AMs either at T2 or T3 (the data for T1 were not available).

4.2.3.2. Longitudinal trajectory of coherence

According to the results of the coherence analysis, only the 2- and 4-Hz AM rates were selected for the longitudinal analysis, since no significant coherence was found in the 30-Hz AM rate at any testing time. Regarding the selection of the electrodes, although previous similar studies have averaged electrode values in the left and the right hemispheres (De Vos et al., 2017; Vanvooren et al., 2014), visual inspection of the data for the 2-Hz AM (Figure 4.2.2) suggested that coherence did not develop equally in the different ipsilateral electrodes. To test the possibility that coherence developed differently as a function of electrode, we did not average coherence values per hemisphere, but introduced an Electrode factor. For comparability reasons, we did not average coherence values of intra-hemispheric electrodes for the 4-Hz AM either, although the differences among hemispheres were not so clear (Figure 4.2.3).

Electrode selection was based on previous MEG results at the source and sensor level, which have found coherence to be most prominent in temporal areas (J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015). Since our sample size did not allow us to introduce all temporal and parietal electrodes and estimate a reliable model (i.e. this would lead to a poor participants-to-observations ratio and consequent convergence issues), we further reduced the array of electrodes to temporal (T7 and T8) and closest-to-temporal parietal electrodes (P7 and P8). Moreover, this decision was assisted by the fact that these two pairs of electrodes showed the highest mean coherence at T3 for both AM rates of interest (see Table 4.2.1), and the main aim of our analysis was to test the linear increase of coherence values. Finally, to follow-up on the lateralization question we performed multiple Mann-Whitney tests between the electrodes of interest (P7 vs. P8 and T7 vs. T8).

Table 4.2.1. Mean group coherence values (and *SD*) in the electrodes that resulted significant across testing times in the 2- and 4-Hz AM rates

		Electrode								
AM	**Testing time**	**T7**	**P7**	**P3**	**O1**	**Pz**	**T8**	**P8**	**P4**	**O2**
2 Hz	T2	.03 (.03)	.05 (.03)	.03 (.02)	.04 (.03)	-	.04 (.05)	.05 (.04)	.03 (.03)	.03 (.03)
	T3	.04 (.04)	.05 (.05)	.03 (.03)	-	-	.05 (.04)	.04 (.04)	.03 (.03)	-
4 Hz	T1	-	.01 (.01)	-	-	-	-	.01 (.02)	-	-
	T2	-	.02 (.01)	.02 (.01)	.02 (.01)	.02 (.01)	.02 (.01)	.03 (.02)	.02 (.01)	.02 (.01)
	T3	.03 (.03)	.03 (.03)	.02 (.02)	.02 (.02)	-	.03 (.03)	.04 (.03)	.02 (.02)	.02 (.03)

4.2.3.2.1. Coherence to the 2-Hz AM

Electrodes that showed significant coherence to the 2-Hz AM at any testing time were T7, P7, P3, O1, T8, P8, P4 and O2. According to the criteria explained above, we selected electrodes T7, P7, T8 and P8 for further analysis. A visual representation of the developmental trajectory of the coherence in the electrodes of interest can be seen in Figure 4.2.2.

Model specification

As mentioned in section 4.2.2.3.3 (*Longitudinal trajectory of brain-to-speech coherence*), we considered two different models: one that included as fixed effects only the Electrode and Time factors, and another that also included the interaction between them (Time * Electrode). Comparison of the models with and without the interaction indicated that the models were significantly different (χ^2 (3) = 10.15; p = .02). The model with the Time * Electrode interaction had lower AIC (interaction model: 694.64; no interaction model: 698.79) and larger log likelihood (interaction model: -323.32; no interaction model: -328.40). Furthermore, the interaction model was in line with our a priori hypotheses on the putative developmental change in scalp distribution of the coherence maps. The model with the interaction was selected, and therefore the structure of the fixed effects of the final model was formed by the factors Electrode (T7, P7, T8 and P8), Time (2 and 3) and the interaction Time * Electrode.

Regarding the structure of the random effects, the maximally converging model included only the initially planned by-subject slopes for Time and Electrode (to control for interdependent measures), with no intercept. The model included a total amount of 232 observations taken from the data of 34 different subjects.

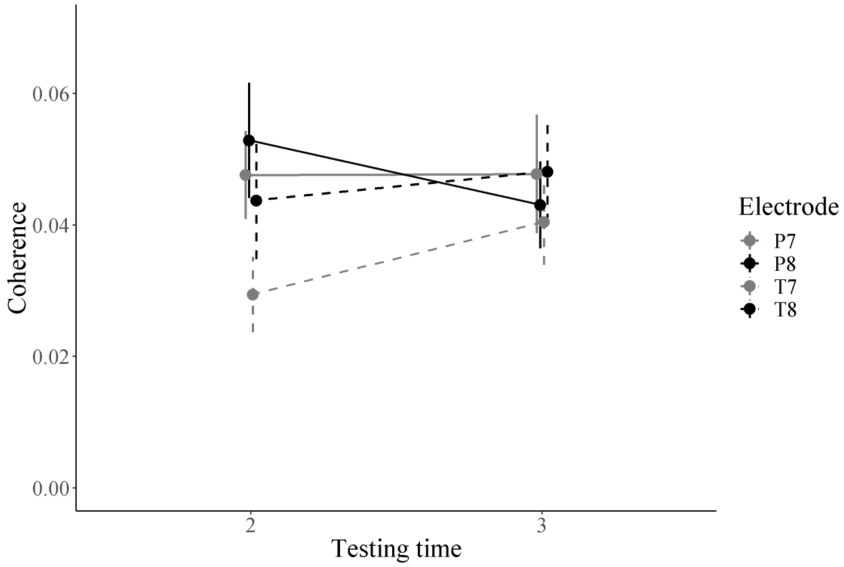

Figure 4.2.2. Development of coherence to the 2-Hz AM in the electrodes of interest from T2 to T3. Vertical bars represent the standard error of the mean. Parietal electrodes are represented with solid lines and temporal electrodes, with dashed lines. Hemisphere is coded in the lines' colour (black: right; grey: left).

Model results

For parsimony reasons, only the results relevant for our hypotheses will be discussed in text. The results for the random effects structure and the least square means (LSM), standard errors and confidence levels (CL) can be seen in Table 4.2.2.a and b, respectively.

Table 4.2.2. Mixed effects model's output with coherence to the 2-Hz AM as dependent variable Time, Electrode and Time * Electrode factors as fixed effects, and by-subject slopes for Time and Electrode as random effects

a. Output for the random effects structure. Reference levels are electrode P7 for the Electrode factor and T2 for the Time factor

Random effect	***SD***
Electrode P7	.03
Electrode P8	.03
Electrode T7	.03
Electrode T8	.04
T3	.03
Residual	.02

b. Fixed effects estimates (least square means), standard errors and confidence levels (.95) for the different levels of the factors Time and Electrode

Time	**Electrode**	**LSM**	***SE***	**df**	**Lower CL**	**Upper CL**
2	P7	.047	.007	40.57	.032	.061
3		.050	.009	33.02	.033	.067
2	P8	.052	.007	38.72	.037	.067
3		.045	.008	36.45	.017	.061
2	T7	.029	.006	40.92	.017	.041
3		.042	.007	35.13	.028	.055
2	T8	.044	.008	37.14	.028	.059
3		.050	.008	31.78	.034	.066

Regarding the difference between the electrodes within the testing times, the only apparent difference seemed to be in electrode T7 against the rest of the electrodes at T2 (see Table 4.2.2.b). Accordingly, the pair-wise corrected contrasts showed that at T2, there was a significant difference between electrodes T7 and P7, and electrodes T7 and P8, such that coherence was lower in electrode T7 in both cases (see complete output of the pairwise contrasts in Table 4.2.3.a). The fact that there was not such difference within T3, and the visual inspection of the estimates and their associated standard errors suggested that there was a significant increase in coherence in electrode T7 from T2 to T3 (T1 β: .029 [*SE* = .006]; T2 β: .042 [*SE* = .007]). Nevertheless, this contrast this not survive the post-hoc Tukey correction (t = -1.68; p = .10; see Table 4.2.3.b for complete output of the pair-wise contrasts). According to our post-hoc analysis, none of the electrodes showed a significant change in coherence from T2 to T3.

Table 4.2.3. Tukey-corrected least square means contrasts

a. Effect of Electrode on Time

Contrast (Electrode)	LSM	*SE*	*t*	*p*
Time 2				
P7-P8	-.001	.006	-.94	.79
P7-T7	.018	.006	2.84	.03*
P7-T8	.003	.007	.43	.97
P8-T7	.023	.006	3.86	.001*
P8-T8	.009	.006	1.36	.53
T7-T8	-.015	.007	-2.19	.14
Time 3				
P7-P8	.005	.005	.88	.82
P7-T7	.008	.006	1.39	.51
P7-T8	-.0003	.006	-.04	1.00
P8-T7	.003	.005	.57	.94
P8-T8	-.005	.006	-.88	.82
T7-T8	-.008	.006	-1.34	.54

b. Effect of Time on Electrode

Contrast (Time)	LSM	*SE*	*t*	*p*
Electrode P7				
2-3	-.003	.008	-.41	.58
Electrode P8				
2-3	.007	.008	.91	.36
Electrode T7				
2-3	-.012	.007	-1.68	.10
Electrode T8				
2-3	-.006	.008	-.813	.42

4.2.3.2.2. Coherence to the 4-Hz AM

Electrodes T7, P7, P3, O1, Pz, T8, P8, P4 and O2 showed significant coherence at any of the testing times at the 4-Hz AM rate. As for the 2-Hz AM rate, we reduced our electrodes of interest to P7, T7, P8 and T8. Figure 4.2.3 shows the developmental trajectory of coherence in the different electrodes of interest.

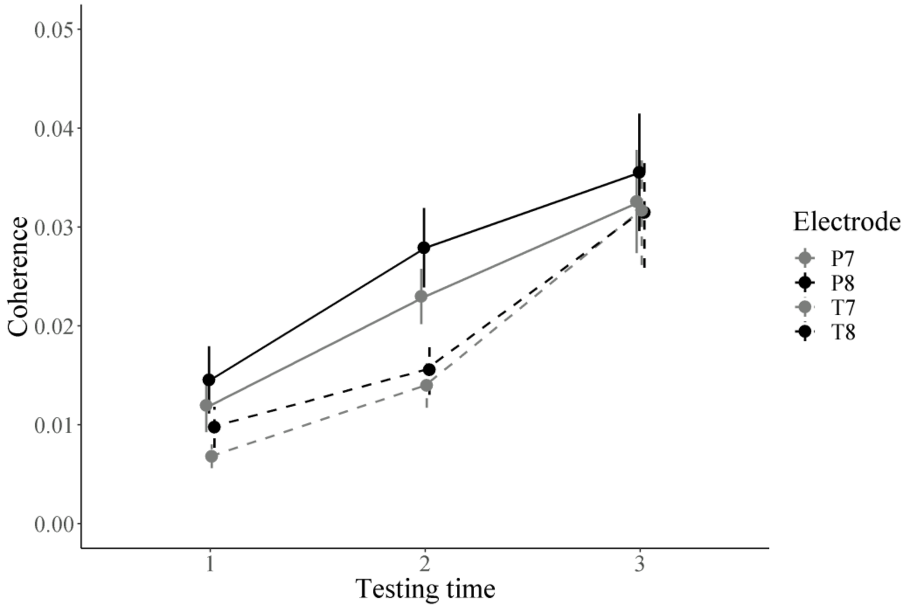

Figure 4.2.3. Development of coherence to the 4-Hz AM in the electrodes of interest from T1 to T3. Vertical bars represent the standard error of the mean. Parietal electrodes are represented with solid lines and temporal electrodes, with dashed lines. Hemisphere is coded in the lines' colour (black: right; grey: left).

Model specification

The results of the ANOVA comparing the models of interest revealed that the model with the interaction Time * Electrode was not significantly different from the model with only the main effects of Time and Electrode (χ^2 (6) = 10.15; *p* = .02), although the model with the Time * Electrode interaction had lower AIC (interaction model: -1752.6; no interaction model: -1752.6) and larger log likelihood (interaction model: 901.31; no interaction model: 906.23). Since visual inspection of the data did not support the presence of an interaction between the Electrode and the Time factors (see Figure 4.2.3), the model without the interaction was selected as the optimal fit of the data given our predictors. The fixed effects of the final model were therefore the factors Time (T1, T2 and T3) and Electrode (T7, P7, T8 and P8).

The maximally converging model included the by-subject slopes for Time and Electrode and an additional by-subject intercept. The model's observation amounted to 332, and the number of different subjects included in the analysis was of 38.

Model results

The complete output of the model can be seen in Table 4.2.4.a and b (random and fixed effects, respectively).

Table 4.2.4. Mixed effects model's output with coherence to the 4-Hz AM as dependent variable, Time and Electrode as fixed effects, and by-subject slopes for Time and Electrode and by-subject intercept as random effects

a. Output for the random effects structure. Reference levels are electrode P7 for the Electrode factor and T1 for the Time factor

Random effect	***SD***
Intercept	.008
Electrode P8	.008
Electrode T7	.005
Electrode T8	.011
T2	.011
T3	.030
Residual	.012

b. Fixed effects estimates (least square means), standard errors and confidence levels (.95) for the different levels of the factors Time and Electrode

Time	**Electrode**	**LSM**	***SE***	**df**	**Lower CL**	**Upper CL**
1	P7	.011	.003	56.26	.006	.017
2		.023	.003	56.52	.017	.029
3		.033	.005	37.02	.022	.043
1	P8	.013	.003	53.79	.007	.020
2		.027	.003	54.89	.021	.034

3		.035	.006	37.35	.024	.046
1	T7	.006	.003	60.66	.001	.012
2		.014	.003	82.76	.009	.019
3		.031	.006	36.80	.021	.042
1	T8	.009	.003	51.56	.004	.015
2		.016	.003	58.27	.009	.022
3		.031	.006	36.70	.021	.042

The results of the LSM analysis showed that there was a significant main effect of Time (Table 4.2.5.a) and a significant main effect of Electrode (Table 4.2.5.a). Accordingly, the statistical tests showed that coherence increased linearly across the testing times. By contrast, the main effect of Electrode was driven by a significant difference between electrodes P8 and T7, such that coherence was larger in the parietal electrode as compared to the temporal electrode across testing times. Although this could point towards an inter-hemispheric difference, the coefficients for other comparisons among parietal and temporal electrodes (P8 vs. T8, P7 vs. T7) suggested that the meaningful difference was between parietal and temporal electrodes, and not between hemispheres.

Table 4.2.5. Main effects of Time (a) and Electrode (b)

a. Main effect of Time

Testing time	**LSM**	***SE***	***t***	***p***
1-2	-.010	.003	-3.49	.005*
1-3	-.022	.005	-4.33	.0004*
2-3	-.012	.005	-2.58	.04

b. Main effect of Electrode

Electrode	**LSM**	**SE**	***t***	***P***
P7-P8	-.003	.002	-1.28	.58
P7-T7	.004	.002	2.22	.13
P7-T8	.003	.003	1.31	.56
P8-T7	.007	.003	2.87	.03*
P8-T8	.006	.003	2.50	.08
T7-T8	-.001	.002	-.44	.97

Follow-up analysis: Assessment of hemispheric differences

Due to the apparent differences in coherence values among the electrodes found for the 2-Hz and the 4-Hz AM rates in T2, and supported by the inter-hemispheric differences found previously in the literature in low-frequency bands (Abrams et al., 2008; Lizarazu et al., 2015; Vanvooren et al., 2014), we performed a follow-up analysis to further examine if the coherence between hemispheres was different for the different conditions across the testing times. Multiple paired Mann-Whitney *t* tests were performed comparing pairs of electrodes from the left and the right hemisphere separately for the different testing times and frequencies of interest. For the 2-Hz band, the only significant difference after FDR correction for multiple comparisons was the activity of electrode T7 vs. T8 in T2 (U = 89; *p* = .03; FDR-*p* = .05), such that coherence was larger in T8 (*M* = .04; *SD* = .05) as compared to T7 (*M* = .03; *SD* = .03). This difference was nevertheless absent in T3 (see Table 4.2.6 for complete output of the multiple t-tests). For the 4-Hz AM rate, no significant difference between any pair of electrodes was found for any testing time (all *p* >.05).

Table 4.2.6. Results of the multiple paired Mann-Whitney *t*-tests comparing pairs of electrodes across testing times and AMs

AM	Testing time	Electrode pair	U	*p*	FDR-*p*
2 Hz	2	P7 vs. P8	168	.86	.86
		T7 vs. T8	89	.03*	.05*
	3	P7 vs. P8	313	.37	-
		T7 vs. T8	231	.55	-
4 Hz	1	P7 vs. P8	131	.42	-
		T7 vs. T8	112	.18	-
	2	P7 vs. P8	152	.57	-
		T7 vs. T8	147	.48	-
	3	P7 vs. P8	234	.59	-
		T7 vs. T8	250	.80	-

4.2.4. Discussion

The aim of the current Experiment was to examine the developmental progression of coherence to amplitude modulations (AM) at rates critical for speech perception. This work shows that, as expected, coherence to AMs at low frequencies (2 and 4 Hz) is already present in very young children. By contrast, at least with our analyses and stimuli, we report that at seven years old do not show coherence to higher frequency bands (30 Hz).

Interesting differences in the developmental trajectory of coherence in the distinct electrodes were found for the 2-Hz and 4-Hz AM rates. While coherence to sounds modulated at the syllabic rate (4 Hz) increased linearly regardless of electrode (and hemisphere) across the three testing times, sensitivity to the prosodic rate (2 Hz) followed a more complex trajectory across T2 and T3. In T2, results of the linear mixed model and of the multiple Mann-Whitney *t*-tests suggested that coherence to the 2-Hz AM rate was biased to the right hemisphere, which was the product of reduced coherence in in electrode T7 (but not in electrode P7). By contrast, the pattern was fully bilateral in T3. This apparent change in laterality is only partially surprising. While previous studies in infants and children suggest an innate right lateralization bias for modulations at the delta rate (De Vos et al., 2017; Telkemeyer et al., 2009, 2011; Vanvooren et al., 2014), studies in adults have shown delta coherence also in the left hemisphere (left inferior gyrus; Molinaro et al. 2016). In our experiment, it is possible that by the time we tested the children at T3, the *delta network* was already distributed across hemispheres. In any case, what we can conclude is that lateralization for linguistic operations is a complex process that will forcefully interact with linguistic experience and the acquisition of new language-related skills. In the gap between T2 and T3, the children in our sample received formal reading instruction for the first time, and it is known that the acquisition of reading shapes brain anatomy and function (Carreiras et al., 2009; Dehaene et al., 2010; Thiebaut de Schotten, Cohen, Amemiya, Braga, & Dehaene, 2014). Lateralization changes with development have been consistently reported from childhood into adulthood (Brown et al., 2005; Holland et al., 2001; Szaflarski et al., 2006), while other studies failed to find such developmental effects (Gaillard et al., 2003; Papanicolaou et al., 2006). It is possible that such contradictory results are in fact due to the specific moment in which the children were tested, and specially to the linguistic experiences they were undergoing in that specific moment. Our results suggest that, at least for language-related auditory perception tasks, the trajectory of lateralization does not follow a simple bilateral to left/right pattern, as previously suggested for other language functions (Friederici et al., 2011; Holland et al., 2001). Instead, lateralization to the prosodic modulations of speech seems to be a dynamic process characterised by the cooperation of the hemispheres when confronted with new linguistic challenges, such as reading.

Regarding coherence to the 4-Hz AM rate, although we found significant differences between the electrodes across testing times, these were not between inter-hemispheric pairs (P7 vs. P8 and T7 vs. T8), but mainly between parietal and temporal electrodes (significant difference between electrodes P8 and. T7; marginal difference between P8 and T8), such that activity was larger in parietal as opposed to temporal electrodes. Nevertheless, due to the exploratory nature of this work it is difficult to draw final conclusions on the functional meaning of the differences in coherence among the electrodes. In any case, the Mann-Whitney *t*-tests did not throw significant inter-hemispheric differences in coherence to the syllabic (4 Hz) rate at any testing time, and these results are in principle at odds with previous evidence reporting that five-years-old children’s sensitivity to this modulation rate is already right-lateralised, and no significant changes are present at least until they are nine years of age (De Vos et al., 2017; Vanvooren et al., 2014). Nevertheless, these studies measured children’s ASSR, a power measure, and the comparisons of their and our results should be performed with caution. Whereas coherence has been consistently reported as a measure of communication between distant brain areas, amplitude is supposed to measure local changes in the activity of populations of neurons (Fries, 2005; Nunez & Silberstein, 2000). Overall, given the putative differences in the underlying brain processes that amplitude and coherence measure, it is difficult to establish links between the current study and previous studies using similar stimuli but different measures (De Vos et al., 2017; Vanvooren et al., 2014). In addition, several studies in adults found left-lateralised responses to the syllabic envelope (4-7 Hz) of intelligible speech (Howard & Poeppel, 2012; Peelle et al., 2013). Due to the mixed evidence, what we can conclude is that, using a measure with which laterality effects have been found in adults (e.g. Lizarazu et al., 2015), no differences in lateralization were found for the 4-Hz AMs in young children from four to seven years of age. The moment at which right-lateralised coherence to the syllabic rate appears during development is, again, an empirical question that should be addressed in future studies.

The different developmental trajectory between the syllabic (4 Hz) and the prosodic (2 Hz) AM rates is not surprising. Accumulating evidence supports the idea that these bands might have a different functional meaning for speech processing, such that while the theta band would reflect lower-processes related mainly to the acoustic features of the signal (i.e. tracking of the syllabic rhythm of speech), the delta band would code for higher-processes specifically related to language (Keitel, Gross, & Kayser, 2017; Molinaro et al., 2016; Molinaro & Lizarazu, 2018; Vander Ghinst et al., 2016). For example, Molinaro & Lizarazu (2018) found coherence differences while listening to speech as opposed to other auditory stimuli (AM signals and rotated speech) in the delta (0-1 Hz) but not in the theta band (6-7 Hz), such that coherence to speech was larger in the delta band as opposed to the rest of conditions (i.e., non-linguistic auditory stimuli) in right temporal but also in left frontal regions, while coherence in the theta band was similar across conditions (speech and non-linguistic auditory stimuli), regardless of their nature. Our results suggest that the difference across frequency bands might already present in early childhood, although future studies should further explore its functional meaning.

The fact that we found coherence at the lower but not at the higher frequency modulations goes in line with previous evidence reporting that young children are more sensitive to the slow as opposed to the fast rhythms of speech, and that the latter should increase as reading experience accumulates (Anthony & Francis, 2005; Morais et al., 1987; Ziegler & Goswami, 2005). Nevertheless, we expected that coherence to the fast rates would already be moderately established at T3, but that was not the case. This could be due to the fact that when children were tested the last time, they had received only one year of formal reading instruction, and fine-grain sensitivity to the phonemic rate might need more training to be fully developed, at least to be detectable with the coherence measure we used. Indeed, using an amplitude measure and a modulation rate at 20 Hz (beta band), the longitudinal study by De Vos et al. (2017) did find an increase in the ASSR after children had acquired reading (from five to seven years old), suggesting that the increase in neural synchronization to the fast modulations of speech might be more visible in terms of power, as compared to phase. Supporting this, previous studies in adults using linguistic stimuli have found gamma power synchronised activity in response to the phonemic rate of speech, but not phase synchronization, which was found only at lower (delta and theta) rates in response to the syllabic and prosodic temporal components of speech (Gross et al., 2013; Park et al., 2015). Furthermore, the idea that coherence to the fast modulations of speech also increases with age is supported by a previous cross-sectional study which reported a significant difference in coherence to signals modulated at 30 Hz between older (from eight to 14 years old) children and adults, such that the adults showed higher phase-locking values (PLV) as compared to the children (Lizarazu et al., 2015). Nevertheless, the authors only report group comparisons, and no information on the significance of the coherence in the separate groups is available. Lastly, the fact that brain oscillatory activity in response to signals modulated at high frequencies increases with age is supported by anatomical studies showing a general increase in white matter from childhood into adulthood (see Paus et al., 2001 for a review), with an increase in neural pathways supporting auditory processing from five years of age into adulthood (Lebel, Walker, Leemans, Phillips, & Beaulieu, 2008). In conclusion, longitudinal research following up the children until they are older might reveal the time point at which coherence to high frequencies is fully established, and importantly unravel the cognitive correlates of such neural shift.

Although, as for the Natural speech experiment (see Experiment 1), the coherence values we report for the children are relatively small, showing that coherence can already be measured in very young pre-reader children is *per se* a relevant result for the literature on language development. Indeed, the tight relation between reading skills and coherence to natural speech and language-relevant AMs previously shown in older children and adults (Abrams et al., 2009; J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Molinaro et al., 2016; Power et al., 2016, 2013) suggests that this measure could become a neural marker for the prognosis and early intervention of developmental reading disorders. In this line, Experiment 3 will explore the value of coherence to syllabic- and prosodic-rate AMs for the development of reading.

Conclusions of Experiment 2

In this experiment we report evidence that auditory signals modulated at the syllabic (4 Hz) and prosodic (2 Hz) rates trigger phase coherent activity in the child's brain, and that such activity follows a differential developmental trajectory in the different frequency bands. No significant increase of coherence to the 2-Hz band was detected from T2 (5-6 years old) to T3 (6-7 years old), but the results suggest a change in lateralization during this interval, coinciding with the period in which children received reading instruction. By contrast, a significant bilateral linear increase in coherence was found for the 4-Hz band from T1 to T3. This work highlights the existence of an interaction between lateralization patterns and linguistic experience. Finally, no significant coherence was found in the higher-frequency range (30 Hz), suggesting that at this age, children are still more sensitive to the slow as compared to the fast rhythms of acoustic signals, at least in terms of phase coherence.

4.3. Experiment 3: The contribution of brain rhythmic activity in response to auditory stimuli for early reading development

4.3.1. Introduction

Recent accounts of developmental dyslexia assign abnormal cortical oscillations in response to the different rhythms of speech a causal role in the acquisition of inappropriate phonological representations and subsequent reading (e.g. Goswami, 2011; Lallier et al., 2017; Lehongre et al., 2011). Although the links between oscillatory processing and reading acquisition have already been reviewed in the chapter devoted to the theoretical background in which this doctoral work is framed (Chapter 1), a brief recapitulation will be presented here in the interest of clarity. The acquisition of the ability to map individual speech sounds (phonemes) to their arbitrary written representations (graphemes) is a milestone for reading acquisition and has been shown to depend tightly on children phonological awareness, i.e. on the ability to consciously understand that the speech signal is constituted by individual sounds and their combinations (Vellutino et al., 2004). Accordingly, most of dyslexic individuals show deficits in some aspect of phonological processing (Landerl et al., 2013; Ramus, 2003). Nevertheless, a central question remains unanswered, namely what is the origin of the phonological deficit in dyslexia. To answer this question, scientists have taken a step back in development and looked into the child’s ability to perceive speech before reading acquisition. Relevant findings have been made in this field, such that the perception of the speech slow rhythms, which is an important cue for the segmentation of the continuous speech signal in its constituents (Ramus et al., 2000), has been consistently shown to be impaired in dyslexic individuals (Corriveau et al., 2010; Huss et al., 2011; Richardson et al., 2004; Thomson et al., 2006). Following this evidence, it has been proposed that the phonological problems of dyslexic individuals would be a consequence of abnormal processing of the slow changes in amplitude in the speech signal (which generate the slow rhythms of speech), such that a deficit in sampling the slow temporal components of speech would lead to abnormal segmentation of the speech signal, which would eventually derive in atypical fast (phonemic) processing and in the formation of an inappropriate representation of phonemes (Goswami, 2011, 2018; Lallier et al., 2018, 2017). In neural terms, the *transfer* of the deficit from the slow to the fast temporal components of speech is supported by recent neurophysiological findings showing that brain activity in high frequencies (e.g. gamma) seems to be modulated by activity in lower frequencies (delta and theta) in a phenomenon known as *cross-frequency coupling* (Canolty et al., 2006; Gross et al., 2013; Lakatos et al., 2005). Indeed, if temporal processing in the brain works in a hierarchical manner with low frequencies (which code for stress and syllabic information) governing the activity of high frequencies (which code for phonemes and phonemic contrasts), it is not surprising to hypothesise that a deficit in slow temporal processing would also derive in abnormal processing of speech at fast temporal rates (Goswami, 2011).

Here it is important to note that alternative theoretical lines suggest that the problem of dyslexic individuals would not lie in an abnormal synchronization to the slow rhythms of speech, but in sampling of high-frequency information at the phoneme rate, which would in turn derive in under-specification of phoneme entities (De Vos et al., 2017; Lehongre et al., 2011, 2013; Poelmans, Luts, Vandermosten, Boets, et al., 2012). In any case, either as primary deficit (Lehongre et al., 2011) or as a consequence of abnormal processing of low-frequency information (Goswami, 2011), both theoretical accounts would manage to adapt a deficit in high-frequency processing. By contrast, while the hypothesis claiming only high-frequency sampling would assume that processing at low frequencies should be preserved (Lehongre et al., 2011, 2013), Goswami (2011)'s proposal would claim for a (primary) deficit at these low frequencies. Evidence in favour of both hypotheses has been provided and, unfortunately, the current state of the literature does not allow drawing final conclusions due to methodological differences among the studies. Nevertheless, the fact is that multiple studies have reported abnormal oscillatory activity in dyslexic individuals using auditory natural speech and other linguistic stimuli (Abrams et al., 2009; Lehongre et al., 2013; Molinaro et al., 2016; Power et al., 2016, 2013) as well as non-linguistic acoustic signals amplitude-modulated (AM) at rates relevant for speech perception, both at high and low-frequency bands (De Vos et al., 2017; J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Poelmans, Luts, Vandermosten, Boets, et al., 2012).

In the interest of clarity, Table 4.3.1 provides a summary of the cross-sectional results of the studies comparing dyslexic and control readers that will be briefly reviewed in the next sections. Please note that the enummeration of studies does not intend to be exhaustive, but just to exemplify the abundance of mixed evidence in the literature. Moreover, the table presents only the results that are relevant for our own experiment (see specific publication for complete details).

Brain oscillatory activity in response to AM signals

Impaired oscillatory responses both in terms of phase and power at the stress (delta), syllabic (theta) and phonemic (high-beta and gamma) rates have been found in dyslexic as compared to control readers using non-linguistic AM stimuli (De Vos et al., 2017; J. A. Hämäläinen et al., 2012; Lehongre et al., 2011; Lizarazu et al., 2015; Poelmans, Luts, Vandermosten, Boets, et al., 2012). For example, J. A. Hämäläinen et al. (2012) compared adult dyslexic and control participants' oscillatory responses to signals modulated at 2, 4, 10 and 20 Hz and reported that dyslexic individuals showed reduced phase locking value (PLV) to the 2-Hz AMs in the right hemisphere and larger PLV at 10 Hz in the left hemisphere (no differences were found at either 4 or 20 Hz). The authors interpreted larger oscillatory responses at 10 Hz in the dyslexic group as a compensatory mechanism for the abnormal entrainment at 2 Hz. By contrast, Lehongre et al. (2011) found that dyslexic individuals showed reduced power synchronization in the left hemisphere in the 25-35 Hz band (high beta-low gamma), and that left-asymmetry for processing modulations at the phonemic rate correlated positively with behavioural measures of phonological processing (Lehongre et al., 2011). Supporting Lehongre et al. (2011)'s result, a study using auditory steady state responses (ASSRs) in response to signals modulated at 4, 20 and 80 Hz found reduced ASSR strength to the 20-Hz AM rate in the left hemisphere in dyslexic adults when compared with control readers, while no differences were found for modulations at 4 or 80 Hz (Poelmans, Luts, Vandermosten, Boets, et al., 2012). Furthermore, general amplitude strength to the 20-Hz modulation regardless of hemisphere correlated positively with phonological skills.

Table 4.3.1. Summary of cross-sectional studies comparing dyslexic individuals and controls' oscillatory activity as a function of the measure used (power vs. phase). a) shows studies using non-linguistic stimulation and b) studies using linguistic stimulation

a. Non-linguistic stimulation (AMs)

Study	**Participants**		**AM rate**	**Technique**	**Analysis**	**Results**			
	n	**Age (~*M*)**				**DD vs. TD**	**Freq (Hz)**	**Hem**	**Lat**
				Power					
Lehongre et al. (2011)	TD: 21 DD: 23	TD: 24 DD: 27	10-80	MEG	ASSR	Reduced	25-35	Left	
Poelmans, Luts, Vandermosten, Boets, et al. (2012)	TD: 30 DD: 30	TD: 21 DD: 22	4 20 80	EEG	ASSR	Reduced	20	Left	
De Vos et al. (2017)	TD: 54 DD: 14	TD & DD: 7 and 9*	4 20 80	EEG	ASSR	Increased	20	Bilateral	
				Phase					
J. A. Hämäläinen et al. (2012)	TD: 10 DD: 11	TD: 28 DD: 22	2 4 10 20	MEG	PLV	Reduced	2	Right	
						Increased	10	Left	
Lizarazu et al. (2015)	TD(C): 10 DD(C): 10 TD(A): 11 DD(A): 11	TD(C): 12 DD(C): 11 TD(A): 32 DD(A): 30	4 7 30 60	MEG	PLV	Increased	4	Bilateral	TD: Right DD: Bilateral
						Increased	30	Right	TD: Bilateral DD: Right

* The study by De Vos et al. 2017 was longitudinal, but only the cross-sectional results within the testing times are presented. See text for more information.

b. Linguistic stimulation

Study	Participants		Stimulus type	Technique	Analysis	Results		
	n	**Age (~*M*)**				**DD vs. TD**	**Freq (Hz)**	**Hem**
				Power				
Lehongre et al. (2013)	TD: 15 DD: 17	TD: 24 DD: 24	AV speech (movie)	EEG/fMRI	Correlation EEG power-BOLD time course	Reduced	25-35	Left
				Phase				
Abrams et al. (2009)	GR: 8 PR: 8	GR: 12 PR: 13	3 speech modes: conversational, clear and compressed	EEG	Cross-correlation envelope-brain signal	(compressed speech only) GR: Right-lateralised PR: Bilateral	-	-
Power et al. (2013)	TD: 21 DD: 11	TD: 14 DD: 14	Syllable in 3 conditions: auditory, visual and AV	EEG	ITC	N.D.		
Power et al. (2016)	CA: 23 RA: 11 DD: 12	CA: 13 RL: 9 DD: 16	8-channel noise-vocoded sentences	EEG	Stimulus envelope reverse reconstruction	Reduced	0-2	Bilateral
Molinaro et al. 2016	TD(C): 10 DD(C): 10 TD(A): 10 DD(A): 10	TD(C): 12 DD(C): 11 TD(A): 33 DD(A): 30	Normal sentences	MEG	Coherence	Reduced Reduced	0.5-1	Right (AC) Left (IFG)

AC = auditory cortex; AV = audiovisual; CA = controls matched in age; DD = developmental dyslexics; Freq = Frequency; GR = Good readers; Hem = hemisphere; IFG = inferior frontal gyrus; ITC = inter-trial coherence; Lat = Lateralization; PLV = phase-locking value; PR = Poor readers; RA = controls matched in reading level; TD = typically developing

Here it is important to note that contradictory results among studies could be rooted in methodological differences, such that studies finding a deficit in low frequencies used phase coherence measures (J. A. Hämäläinen et al., 2012), while studies finding a deficit in higher frequencies used power synchronization measures (Lehongre et al., 2011; Poelmans, Luts, Vandermosten, Boets, et al., 2012). For this reason, these results could be taken as complementary rather than contradictory. In any case, a later study using phase measures (PLV) provided evidence that dyslexic children and adults showed abnormal synchronization to both low (theta) and high (gamma) frequencies (Lizarazu et al., 2015). In this study, the authors compared dyslexic and control children and dyslexic and control adults. The authors report that dyslexic participants showed larger PLV to the 4-Hz band as compared to controls regardless of age and that furthermore, while PLV for this frequency band was larger in the right hemisphere in control participants, coherence was bilateral in dyslexics. The degree of the PLV right-lateralization to the 4-Hz band correlated positively with non-word and word reading times within the control group, while such correlation was not present within the dyslexic group. Regarding the 30-Hz band, a hemisphere by group interaction was found, such that entrainment to this band was larger in the dyslexic participants in the right hemisphere, while no difference between hemispheres was found for control participants (suggesting bilateral sensitivity to high frequencies in normal readers). Nevertheless, no correlation between the reading/phonological measures and the PLVs at 30 Hz was found.

Overall, although the results of these studies might seem contradictory due to methodological differences, it is clear that the functional role of lateralization biases for auditory temporal processing cannot be underestimated, since hemispheric differences that correlated with phonological/reading skills have been found between groups of typical and of dyslexic children and adults both at low (J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015) and high AM rates (Lehongre et al., 2011; Poelmans, Luts, Vandermosten, Boets, et al., 2012).

It is important to note that all the studies reviewed above tested participants who (with or without limitations) could already read. However, to provide evidence on the causal role of auditory temporal processing for reading acquisition, studies testing pre-readers at risk of developing dyslexia and/or children before and after they are exposed to formal reading instruction are needed. In this line, a study comparing five-year old pre-readers with and without familial risk to develop dyslexia did not find any group difference in the strength of the ASSRs for modulations at 4 or 20 Hz (Vanvooren et al., 2014), while only small differences were found at the 80 Hz modulation, such that responses were less lateralised to the right hemisphere in the group of high-risk as compared to the low-risk group of children. These same children were further tested at seven (beginning readers) and nine (more advanced readers) years of age, when some of them had already been diagnosed with dyslexia (De Vos et al., 2017). From the longitudinal perspective, the authors report again no group differences for the syllabic modulation rate (4 Hz). The only effect they found for this band was a right lateralization bias in all children and testing times, such that synchronization to the syllable rate was not modulated by group and did not increase with age, at least in terms of ASSRs (but see our results of Experiment 2). By contrast, they found a main effect of age and of hemisphere for the 20 Hz AM, such that the response increased with age and was right-lateralised across the testing times. Very interesting relations were found between the developmental change in power response to the 20 Hz modulation rate (i.e. the subtraction of the pre-reading activity from the activity at 7 or 9 years old, respectively), such that children with a larger increase in power for the 20 Hz band from the pre-reading to the later reading stages showed poorer reading and phonological skills. When dyslexic children and controls were compared, they found that regardless of hemisphere, dyslexics showed a larger response to the 20 Hz band both when they were seven and nine years of age, but not when they were five. This suggested that the increase in response to the 20-Hz band was related to reading instruction, and that a larger response (as well as a larger developmental increase from pre-reading to reading stages) was related to the abnormal sampling of phonemic information that characterises dyslexia.

Brain oscillatory activity in response to linguistic stimuli

A possible limitation of the studies mentioned above is the use of non-verbal stimuli. Evidently, if abnormal auditory processing in dyslexia is related to phonological processing, it must also be shown with stimuli that actually contain phonological information (i.e. verbal stimuli). In this context, dyslexic children and adults have been reported to show abnormal oscillatory encoding of the speech amplitude envelope at the delta (Molinaro et al., 2016; Power et al., 2016), at the theta (Abrams et al., 2009) and at the gamma (Lehongre et al., 2013) bands.

Regarding deficits at the delta band, Molinaro et al. (2016) reported that dyslexic children and adults showed reduced phase synchronization to sentences in the right auditory cortex (RAC) and the left inferior frontal gyrus (LIFG) as compared to control participants in the 0.5-1 Hz band. Another study testing dyslexic children and two groups of typically developing children (matched either in reading abilities or in age) showed that the sensitivity of the brain to encode the envelope of noise-vocoded sentences at the 0-2 Hz frequency range (delta band) correlated positively with their phonological awareness, such that the better the neural encoding of the envelope at the delta band, the better the phonological skills (Power et al., 2016). By contrast, a study by the same lab (Power et al., 2013) testing 13 years-old children's auditory oscillatory responses to a signal consisting of the rhythmic repetition (at 2 Hz) of the syllable /ba/ found no differences in inter-trial coherence (ITC) in the delta band between dyslexic and control readers. Differences were found though in the timing of the response, such that the brain responses of dyslexic readers were delayed as compared to controls. The absence of differences in coherence values in the delta band contrasts with the studies reviewed above (Molinaro et al., 2016; Power et al., 2016). Nevertheless, it is important to note that, although the stimulus used by this last study was *linguistic*, it is difficult to compare activity in response to natural speech with activity in response to a rhythmically presented syllable. Among the many differences that could be highlighted (lexical, semantic, etc.), there is a difference between these types of stimuli that is very relevant for the phenomenon studied here, namely their difference in temporal predictability. While the stimuli used in Power et al. (2013) were purely rhythmic (and hence purely expectable), the natural speech used by studies finding differences in the delta band (Molinaro et al., 2016; Power et al., 2016) used natural speech, whose envelope, though pseudo-rhythmic, is not as predictable as the one of a syllable presented rhythmically. Accordingly, temporal processing of the natural speech stimuli could be more challenging as compared to temporal processing of the rhythmic presentation of syllables, and under some circumstances, the delta-activity deficit of dyslexic readers could appear just in more challenging situations (Power et al., 2013; but see J. A. Hämäläinen et al. 2012).

Differences between dyslexic and typically developing children have also been found in in the theta band in response to time-compressed sentences, but not to clear speech (Abrams et al., 2009). Interestingly, the differences reported in this study referred to lateralization patterns, such that reduced right lateralization of the responses to the envelope at the syllabic rate (theta band) predicted poor reading skills in children (Abrams et al., 2009). This last study, together with the study by Molinaro et al. (2016), which also found differences between dyslexic and control readers in RAC coherence in the delta band, suggest that, more than a general impairment in oscillatory activity, abnormal lateralization of oscillations in response to the slow components of speech could be at the roots of dyslexia. Nevertheless, other studies did not report or find lateralization differences between groups (Power et al., 2016, 2013).

Abnormal oscillatory activity in the left hemisphere in high-frequency bands (25-35 Hz) in response to linguistic stimuli has also been reported using a combined EEG-MRI design (Lehongre et al., 2013). Contrary to previous studies, the authors found that there were no group differences in right hemisphere power synchronization to the delta (1-3 Hz) or the theta (4-7 Hz) bands while exposed to audio-visual speech, such that right dominance for these low frequencies was present in all participants regardless of group. By contrast, they found a difference in the high beta-low gamma band (25-35 Hz), such that dyslexic readers' responses to the high-frequency components of speech were reduced as compared to the controls' in the left hemisphere. These results are clearly at odds with the studies mentioned above, since differences were only found in the left hemisphere for the gamma band, while no differences in right hemisphere responses in low-frequency bands (delta and theta) were found. Nevertheless, there are clear methodological differences between the studies. The previous studies (Abrams et al., 2009; Molinaro et al., 2016; Power et al., 2016, 2013) used either MEG or EEG and assessed brain oscillatory activity with coherence measures (PLV, coherence, etc.), whereas the study by Lehongre et al. (2013) used correlations between the EEG power and the BOLD signal time course. Importantly, EEG power/BOLD correlations allow a better signal to noise ratio for high frequencies, as opposed to phase coherence with the envelope of speech, which is optimal to explore activity in low frequencies (Howard & Poeppel, 2012). This difference might have been crucial for the contradictory results found.

Lastly, all the studies reviewed so far involved testing dyslexic readers. However, if theories that claim for a general relation between auditory oscillatory activity and reading acquisition (Goswami, 2011; Lallier et al., 2017; Lehongre et al., 2011) are in the right path, such relation should also be present in typically developing children. Evidently, this would only be true if we consider dyslexia as the end of the reading continuum, and not as a separate category. To our knowledge, only one study tested auditory entrainment only in typically developing children (mean age: approx. 14 years old) using coherence measures (Power et al., 2012). This study measured children's oscillatory responses to the rhythmic presentation of the syllable /ba/ in different modalities (auditory only, visual only and audio-visual) and found that phase coherence in the auditory only condition correlated positively with written language measures, but not with phonological measures (Power et al., 2012). Although the authors do not discuss these results in depth, it is important to highlight that there is an obvious difference between testing children with language impairments and typically developing children, namely the variance in performance (larger for the clinical group). Consequently, the absence of correlations in this study could be due to reduced variance of the children in the phonological tasks. Supporting the importance of the contribution of oscillatory activity also for normal reading development, the study by Lizarazu et al. (2015) did find a correlation between the degree of right lateralization to the 4-Hz band and non-word/word repetition only for their group of typical readers regardless of age. Again, the fact that the correlation was found with a lateralization measure suggests that inter-hemispheric differences in oscillatory activity might be more predictive of reading performance as opposed to whole-brain values of oscillatory activity (Goswami, 2011; J. A. Hämäläinen et al., 2012; Lehongre et al., 2011, 2013).

Natural speech vs. non-linguistic AMs

The fact that abnormal oscillatory activity, and specially lateralization differences, have been found in dyslexic readers in response to both linguistic and non-linguistic stimuli (e.g. Lehongre et al., 2013; Lizarazu et al., 2015; Molinaro et al., 2016; Poelmans, Luts, Vandermosten, Boets, et al., 2012) suggests that the deficits in temporal processing in dyslexia are not restricted to verbal processing, but visible as soon as critical speech modulations (even deprived of phonological information) are tested. Nevertheless, it is not clear if results coming from these two sources of evidence are directly comparable, or more specifically if brain oscillatory responses to these two types of stimuli are functionally equivalent. Supporting this, a very recent study comparing coherence to natural speech and to AM signals at the delta (0-1 Hz) and at the theta band (6-7 Hz) with MEG found that coherence was not different between the speech and non-linguistic conditions in the theta band, while delta band coherence was larger in right temporal and left frontal regions for the verbal as compared to the non-verbal condition. This evidence suggests that coherence in the theta band could be more generally related to auditory processing, while delta band coherence might be engaged in higher level processes related to specific language processing.

This study

In spite of the putative relevance of brain oscillatory activity in response to auditory stimuli for the development of reading, only one study has tried to assess its longitudinal contribution to reading acquisition comparing dyslexic with control readers and using power measures and non-linguistic stimuli (De Vos et al., 2017). By contrast, no study has measured the contribution of auditory temporal processing for the development of reading in a sample of typically developing children and using phase coherence measures. Furthermore, none of the studies testing the relation between oscillatory activity and reading used both linguistic (with phonological information) and non-linguistic (without phonological information) stimuli to compare their contribution to reading. However, given the apparent specifically linguistic function of delta band entrainment (Molinaro & Lizarazu, 2018), this comparison might yield interesting results that would enrich our knowledge on the role of oscillatory activity specifically related to verbal processing for the acquisition of reading.

Our aim with this experiment was to fill these gaps in the literature. To do so, we tested children before (T1 and T2) and after reading was introduced in the school curriculum (T3). Coherence to Natural speech and to AM signals was tested via EEG at all testing times (see Experiments 1 and 2), while reading achievement was tested only at T3.

Hypotheses

To our knowledge, only one study has tested the longitudinal contribution of early brain oscillatory activity for later reading development in young children, and using power measures and non-linguistic stimuli (De Vos et al., 2017). Furthermore, this study compared typically developing children with children who were initially at familial risk of dyslexia, from whom some later developed dyslexia. By contrast, the contribution of early brain oscillatory activity to *exclusively* typical reading development has not been yet assessed. Given these circumstances, our hypotheses for the relation between coherence to natural speech and reading were based on cross-sectional results in adults and older children with dyslexia. We expected reading achievement to be positively correlated with brain-to-speech coherence in the delta band (Molinaro et al., 2016; Power et al., 2016) and/or in the theta band (Abrams et al., 2009) at least when children could already read, i.e. within T3. Nevertheless, our predictions on the different contribution of left- *versus* right-hemisphere coherence in low-frequency bands to explain reading variance were not clear, given that either bilateral (Power et al., 2016) or specific right-hemisphere (Abrams et al., 2009; Molinaro et al., 2016) impairment in speech envelope encoding has been found in children with dyslexia.

Regarding our non-linguistic stimuli, we based our predictions within T3 in transversal studies comparing typical and dyslexic readers that found differences in coherence to AM signals in the delta (J. A. Hämäläinen et al., 2012), in the theta (Lizarazu et al., 2015) and in the gamma (Lehongre et al., 2011) bands. Accordingly, we expected coherence at these frequency ranges to correlate significantly with reading skills at T3.

Finally, regarding our developmental predictions, we expected significant longitudinal correlations between oscillatory activity in pre-reading stages (T1 and T2) and future reading skills (T3) based on the previous study by De Vos et al. (2017). According to this study, we also expected developmental changes in coherence to be correlated with reading achievement. Nevertheless, we also considered the possibility that our results might be at odds with De Vos et al. (2017)'s work, given the methodological differences (power vs. coherence measures) between ours and their study.

4.3.2. Materials and methods

4.3.2.1. Participants

Coherence to Natural speech and reading

Twenty-seven children of the original sample completed the EEG task testing coherence to Natural speech at T1 and the reading tasks at T3 (age *M* = 5.08; *SD* = .30; 13 males). From these children, 20 were Basque dominant and seven were Spanish dominant. Four of the children were left-handers.

At T2, 29 children (age *M* = 5.87; *SD* = .31; 16 males) completed the EEG and the reading tasks. Nineteen of these children were Basque dominant and 10 Spanish dominant. Four children were left-handers.

Finally, 32 children completed the reading and EEG task at T3 (age *M* = 6.98; *SD* = .32; 16 males). Twenty-two and 10 children were characterised as Basque or Spanish dominant, respectively. Four of the children were left-handers.

Coherence to amplitude-modulated (AM) signals and reading

Regarding the EEG task measuring coherence to the AM signals, at T1, 27 of the children completed both the EEG at T1 and the reading tasks at T3 (age *M* = 5.10; *SD* = .33; 11 males). Eighteen and nine of these children were Basque or Spanish dominant, respectively. Three children were left-handers.

Thirty-one of the children completed both the EEG at T2 and the reading tasks at T3 (age *M* = 5.84; *SD* = .32; 16 males). Twenty-one of the children were Basque dominant and 10 were Spanish dominant. Four of the children were left-handers.

Finally, 31 children completed the reading and EEG tasks at T3 (age *M* = 6.98; *SD* = .32; 16 males). Twenty-one children were categorised as Basque dominant and 10 as Spanish dominant. Four of the children were left-handers.

4.3.2.2. Stimuli and procedure

The stimuli and procedure for the Reading tasks can be consulted in section 3.2.2.1.2 of Chapter 3. The general procedure used for EEG acquisition can also be consulted in section 3.2.2.2 of the same chapter. The Stimuli and procedure for the Natural speech task and the AMs task has already been presented in sections 4.1.2.2 and 4.2.2.2 of current Chapter 4 (Experiment 1 and 2, respectively).

4.3.2.3. Data analysis

Similarly, the procedure followed for the separate analysis of the tasks has been presented in section 3.2.4 of Chapter 3, and in sections 4.1.2.3 (Natural speech) and 4.2.2.3 (AM signals) of the current chapter.

Joint analysis of reading and EEG data

First, the EEG and the reading data were transformed into *z*-cores to facilitate comparison among tasks. Thereafter, we computed partial Spearman correlations between our coherence measures for the Natural speech and reading skills, and the AM signals and reading skills, separately.

In all cases, to evaluate the relation between our different measures of coherence (coherence to Natural speech and to AM signals) and reading achievement in T3, we computed partial pair-wise Spearman correlations between reading skills at T3 and the relevant coherence values in temporal electrodes (electrodes T7 and T8). The selection of only the temporal electrodes was based on previous evidence relating reading skills with coherence in auditory areas (J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Molinaro et al., 2016; Power et al., 2016) and on our results showing the most salient (and apparently functional) differences in coherence across testing times in temporal sites of the scalp (see results of Experiments 1 and 2). Nevertheless, to ensure that our correlations between coherence and reading were related to the developmental trajectory of coherence on temporal electrodes only, this same analysis was performed with the parietal electrodes (P7 and P8) for both the Natural speech and the AM signals and its presented in the Appendix (section A2).

Based on previous literature, several analyses were computed with the coherence data in three different forms:

- *Raw coherence*: The raw coherence values in the electrodes of interest at T1, T2 and T3 were used in the correlation analyses. Raw coherence values have been previously used in studies evaluating the relation between coherence and reading abilities (e.g. Power et al., 2016).

- *Coherence change index* (CI)*:* Since coherence changed significantly across the testing times in the electrodes of interest (see results of Experiments 1 and 2), we were interested in examining the putative functional role of these developmental changes from pre-reading to reading stages. To this aim, two CIs in coherence between our separate pre-reading testing times (T1 and T2) and the testing time when children had already received reading instruction (T3) were computed as follows:

$$CI_{13} = Coh_{T3} - Coh_{T1}$$

$$CI_{23} = Coh_{T3} - Coh_{T2}$$

where *Coh* stands for coherence and the numbers in the subscripts for the respective testing times. Correlations between the CIs and the Reading composite measure were then computed. The CI sign indicates the direction of the change, such that a positive sign means an increase in coherence and a negative sign, a decrease. The aim of this analysis was to check if the increase/decrease in coherence was a subtler measure to predict reading achievement as compared to raw measures of coherence. A similar approach in a previous longitudinal study can be seen in De Vos et al. (2017).

- *Lateralization index* (LI): Correlations between reading and reading-related skills and phase coherence measures have been predominantly highlighted with inter-hemispheric differences measures (Abrams et al., 2009; Lizarazu et al., 2015; Molinaro et al., 2016). Therefore, although no significant inter-hemispheric differences were found in brain-to-speech coherence in our sample (see Experiment 1) and the differences in coherence between hemispheres were restricted to the 2-Hz AM signal for the non-linguistic stimulation at T2 (see Experiment 2), we considered the possibility that the lateralization bias in coherence was a subtler measure to capture variance in reading performance. An LI was calculated as follows for each of the testing times:

$$\mathrm{LI} = \frac{Coh_L - Coh_R}{Coh_L + Coh_R}$$

where *Coh* stands for the corresponding coherence value either in the left (*L*) or in the right (*R*) hemisphere, i.e. electrodes T7 and T8, respectively. This measure varies between +1 and -1 values, where positive values signal a left hemisphere bias, and negative values a right hemisphere bias.

When multiple correlations with the same measure were involved in the same analysis, FDR correction was applied, and both *p*-values and FDR-corrected values are reported.

4.3.3. Results

Preliminary results for the reading data were provided in Chapter 3. Similarly, the results of Experiments 1 and 2 of the current chapter describe the results for the different EEG tasks (Natural speech and amplitude modulated signals [AM], respectively). Nevertheless, before presenting the results of the correlations analyses between the EEG and the behavioural reading tasks, a brief summary of the relevant results for the separate tasks will be provided in the following subsections for clarity reasons.

4.3.3.1.Behavioural data (summary)

The Word and pseudoword reading and Text reading tasks correlated highly with each other, and hence a Reading composite measure was created averaging both. Furthermore, descriptive assessment of the *z*-converted data did not suggest that any of the children suffer from any reading-related developmental disorder.

4.3.3.2. EEG data (summary)

4.3.3.2.1. Coherence to Natural speech

The data of five (T1), four (T2) and seven (T3) children included originally in this experiment (i.e. that completed both the Natural speech and the reading tasks) was discarded due excessive artifacts or reduced number of trials (see section 4.1.2 of Chapter 4).

Significant coherence was found in electrode P7 at T1, in electrodes T7, P7, T8, P8 and O2 at T2, and in electrodes T7 and T8 at T3. Electrodes T7, T8, P7 and P8 were selected for the longitudinal analysis. No inter-hemispheric differences were found at any of the testing times. The only significant linear increase in coherence across testing times was found in electrodes T7 and T8.

4.3.3.2.2. Coherence to AM signals

The data of seven children at T1 and T2 and of one child at T3 could not be further analysed after EEG data pre-processing due to artifacts or reduced number of trials (see section 4.2.2 of Chapter 4).

2 Hz

Note that due to a technical issue, the data for the 2-Hz AM was not available for T1. Significant coherence was found in electrodes T7, P7, P3, O1, T8, P8, P4 and O2 at T2, and in electrodes P7, T7, P3, P8, T8 and P4 at T3. Electrodes T7, T8, P7 and P8 were selected for the longitudinal analysis. Coherence was more prominent in T8 as opposed to T7 in T2, whereas no inter-hemispheric differences were detected at T3. No linear increase in coherence between T2 and T3 was detected for any electrode for the 2-Hz AM signal.

4 Hz

Significant coherence was found in electrodes P7 and P8 at T1, in electrodes P7, P3, O1, Pz, T8, P8, P4 and O2 at T2, and in electrodes T7, P7, P3, O1, T8, P8, P4 and O2. Electrodes T7, T8, P7 and P8 were selected for the longitudinal analysis. No inter-hemispheric differences were found at any of the testing times. Coherence increased significantly across the testing times regardless of electrode.

4.3.3.3. Correlation between coherence measures across testing times and reading output at T3

The relation between reading and the different coherence measures is presented separately for the Natural speech experiment (section 4.3.3.3.1) and for the AM experiment (section 4.3.3.3.2).

4.3.3.3.1. Correlations between coherence to Natural speech across testing times and reading output at T3

It is important to bear in mind that we did not find any coherent activity in response to speech at the theta or the gamma bands, and our analyses with reading performance were hence limited to coherence in the delta band (0.5 Hz).

Raw coherence

None of the raw coherence values to speech at 0.5 Hz in the electrodes of interest at T1 correlated significantly with reading outcome at T3 (n = 22; T7: ρ = -.12; p = .60; T8: ρ = .21; p = .34). By contrast, raw coherence values in electrode T8 at T2 correlated significantly with reading outcome at T3 (n = 25; ρ = .52; p <.01; FDR-p = .05), such that children with larger coherence values in this electrode at T2 showed better reading performance at T3 (see Figure 4.3.1). Such relation was not found for the raw coherence values in electrode T7 at T2 (n = 25; ρ = .24; p = .25). Finally, within T3, coherence values did not correlate with reading outcome in any of the electrodes (n = 24; T7: ρ = .15; p = .48; T8: ρ = -.08; p = .71).

Change index (CI)

The coherence CI from T2 to T3 in electrode T8 correlated negatively with reading achievement in T3 (n = 20; ρ = -.44; p = .05; FDR-p = .20), such that children with larger increase in coherence in electrode T8 showed poorer reading performance at T3 (see Figure 4.3.1). Note that this correlation was not significant after FDR correction. No significant correlation between the change in coherence from T2 to T3 was found for electrode T7 (n = 20; ρ = -.13; p = .58). The CI from T1 to T3 did not correlate with reading skills for any of the electrodes (n = 19; T7: ρ = -.26; p = .29; T8: ρ = -.11; p = .64).

Lateralization index (LI)

Reading outcome at T3 did not correlate with the LI neither in T1 nor in T2 (T1: n = 22; ρ = -.09; p = .70; T2: n = 25; ρ = -.21; p = .32).The LI at T3 correlated only marginally with reading scores (n = 24; ρ = .38; p = .07; FDR-p = .21), such that children with larger coherence values to speech at 0.5 Hz in the left as opposed to the right hemisphere at T3 showed a trend to perform better in the reading tasks. Note that this correlation was not marginally significant any more after FDR-correction.

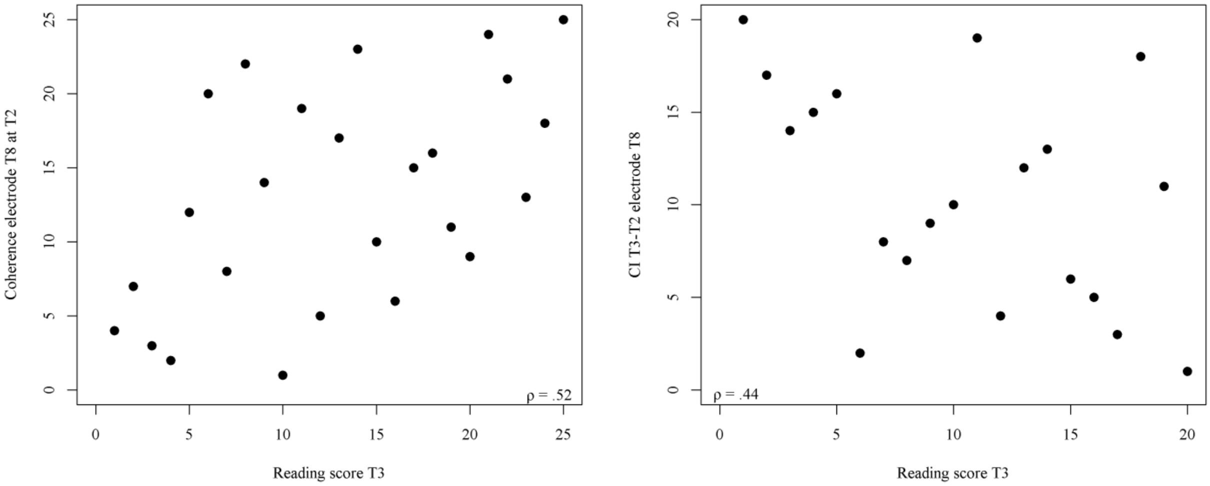

Figure 4.3.1. Correlation between brain-to-speech coherence measures at T2 and reading achievement at T3. The left panel shows the correlation with the raw coherence values and the right panel, the correlation with the CI from T2 to T3.

Coherence in parietal electrodes

As mentioned in the section 4.3.2.3 (*Data analysis)*, we performed the same correlation analyses with the coherence values in the parietal electrodes (P7 and P8). None of the coefficients resulted significant for the raw coherence values, the CIs or the LIs at any testing time (all *p*s >.10; see Table A2.1 in section A2 of the Appendix for complete results).

Follow-up analysis: Phonological processing as a mediator in the reading-rhythm relation

Theories that claim for the existence of a tight relation between coherence to speech and reading development suggest that this relation is mediated by phonological skills (Goswami, 2011; Lallier et al., 2017). Accordingly, we computed the correlation analyses between the coherence values in temporal electrodes across testing times and phonological awareness at T3 (see task description in section 5.1.2.2.4 of Chapter 5). Prior to this analysis, we computed the partial correlation between the Reading composite and the Phoneme deletion/elision task to ensure that they were acceptably correlated. The Spearman correlations between the coherence values and the phonological awareness task were in the same direction as for the Reading composite, but statistical significance of the coefficients was weaker. For parsimony reasons, the results of these correlations can be seen in Table A3.1 in the Appendix (section A3).

4.3.3.3.2. Correlations between coherence to AM signals across testing times and reading output at T3

We did not find coherent brain activity to the 30-Hz AM, and hence we could test the relation between reading and the 2- and 4-Hz bands only.

2 Hz

None of the coherence measures (raw, CI and LI) in temporal electrodes across testing times (T2 and T3) correlated significantly with reading achievement at T3. See table 4.3.2 for complete output of these correlations.

Table 4.3.2. Partial Spearman correlations between reading achievement at T3 and the different coherence measures in temporal electrodes across T2 and T3

a. Raw coherence

				Reading T3	
	Electrode	**Testing time**	**n**	ρ	*p*
Raw Coherence	T7	T2	24	-.15	.49
	T8			-.19	.36
	T7	T3	30	-.22	.25
	T8			-.17	.38

b. CI

			Reading T3	
	Electrode	**n**	ρ	*p*
CI_{23}	T7	23	.13	.57
	T8		-.28	.20

CI = Change index

c. LI

		Reading T3		
	Testing time	**n**	***ρ***	***p***
LI	T2	24	.20	.35
	T3	30	.03	.85

LI = Lateralization index

4 Hz

Similarly to the 2-Hz rate, none of the coherence measures correlated significantly with reading scores at T3 at any testing time (see Table 4.3.3 for detailed results of the correlation analyses).

Table 4.3.3. Partial Spearman correlations between reading achievement at T3 and the different coherence measures in temporal electrodes across T2 and T3

a. Raw coherence

			Reading T3		
	Electrode	**Testing time**	**n**	***ρ***	***p***
Raw coherence	T7	T1	20	-.07	.77
	T8			-.34	.15
	T7	T2	24	-.29	.17
	T8			-.28	.19
	T7	T3	30	-.13	.49
	T8			-.15	.44

b. CI

			Reading T3	
	Electrode	**n**	***ρ***	***p***
CI$_{13}$	T7	19	-.02	.93
	T8		.17	.48
CI$_{23}$	T7	23	.05	.83
	T8		.07	.74

CI = Change index

c. LI

		Reading T3		
	Testing time	**n**	***ρ***	***p***
LI	T1	20	.33	.16
	T2	24	-.03	.89
	T3	30	.20	.29

LI= Lateralization index

Follow-up analysis: Comparison of coherence to speech at the delta band and coherence to signals modulated at the delta band

In light of the contradictory results found for the correlations between reading and our brain measures at the delta band, namely the presence of significant correlations between the coherence to speech at 0.5 Hz (delta) and the absence of significance for the correlations between the coherence at the 2-Hz AM rate (delta), we directly compared these measures to examine whether they were at all related, as it was suggested that they might not reflect fully similar oscillatory functions (see Molinaro & Lizarazu, 2018). Partial Spearman correlations were computed between the coherence to Natural speech at 0.5 Hz and the coherence to the 2-Hz AM in temporal electrodes (T7 and T8) across T2 and T3. As shown in Table 4.3.4, these measures did not correlate with each other at any testing time.

Table 4.3.4. Results of the partial Spearman correlations between the coherence to Natural speech and the coherence to the 2-Hz AM across testing times

	Coherence to speech at 0.5 Hz				
	Electrode	**Testing time**	**n**	***ρ***	***p***
Coherence to 2-Hz AM	T7	T2	23	-.04	.85
	T8			.03	.88
	T7	T3	25	-.17	.41
	T8			.01	.97

4.3.4. Discussion

The aim of this Experiment was to examine the contribution of brain oscillatory activity in response to auditory stimuli for reading achievement. Coherence to natural speech at low frequencies (0.5 Hz) and coherence to amplitude-modulated (AM) signals at the delta and the theta band were analysed prior (T1 and T2) and after (T3) formal reading instruction. First, it is important to note that we show that analysing the coherence phenomenon from different perspectives (raw coherence, change index and laterality index) leads to complementary results that will help characterising the value of the coherence measure in predicting future reading achievement. Furthermore, although our sample size was modest, we were able to detect interesting correlation patterns that should be explored in depth in future studies with larger samples. Regarding the difference between the tasks measuring auditory oscillatory processing, we show that whereas certain measures of coherence to speech captured significant reading variance in our sample, coherence to modulated noises did not.

First, raw coherence to speech in the right hemisphere at T2 predicted reading achievement at T3, such that children with larger coherence values in electrode T8 prior to formal reading instruction (before starting Grade 1) were the ones with better reading scores after finishing Grade 1. This result goes in line with previous cross-sectional results in the dyslexia literature reporting that right-lateralised coherence to the delta frequency components of natural speech correlates positively with reading performance (Molinaro et al., 2016). Moreover, due to its longitudinal nature, this is the first study suggesting a causal relation between them. The contribution of raw right-hemisphere coherence prior to reading instruction was supported by our developmental analysis showing that children with larger increase in coherence in electrode T8 from T2 to T3 were the ones with poorer reading scores. Although this result was not significant after correction, we tend to believe that this was a power issue derived from our modest sample size. In any case, this result is in line with the results of a previous longitudinal study showing that after reading instruction, dyslexic children showed a larger increase in beta band power in response to 20-Hz AM signals as compared to control children (De Vos et al., 2017). We are of the opinion that, although these authors found the increase in power in the beta band while we find it in coherence in the delta band, our results could be complementary rather than contradictory. Indeed, if oscillatory activity in the brain works in a hierarchical manner, with the phase of the slow oscillations modulating the amplitude (power) of the fast oscillations (Canolty et al., 2006; Gross et al., 2013; Lakatos et al., 2005), we could hypothesise that abnormal power oscillatory responses in high-frequency bands could stem from primary deficits in abnormal phase responses in low-frequency bands. Nevertheless, our study was specifically designed to test the development of phase coherence in children and its contribution to reading, reason for which we did not measure power responses or test cross-frequency coupling. Further exploration of the existing data and future studies testing specifically power-coherence relations are needed to provide firm support to this hypothesis. Nevertheless, we believe our result is reinforced by the fact that reading output was not predicted by the increase in coherence from T1 to T3. The fact that the relation was specifically found with the increase between T2 and T3 –the period during which children received reading instruction for the first time– supports the idea that this change was not spurious, but related to reading acquisition itself.

By contrast, we did not find any correlation between coherence in electrode T8 and reading outcome transversally (i.e. within T3). Indeed, right after the first school year of reading instruction, the correlation between reading and coherence tended to be reversed, such that children with better reading were the ones with larger coherence at the delta band in the left hemisphere, according to our lateralization index measure. Although this correlation was only marginally significant and disappeared after correction ($p = .07$; FDR-$p = .21$), we believe it is worth discussing briefly. This result is difficult to interpret due to mixed previous results, such that some studies found that the delta coherence deficit in the auditory cortex in dyslexic readers was restricted to the right hemisphere (Molinaro et al., 2016) whereas other report a bilateral contribution of the delta deficit in temporal sites of the scalp to impaired reading skills in dyslexic children (Power et al., 2016). Furthermore, the study by Molinaro et al. (2016) also found decreased delta coherence in the left hemisphere outside the auditory cortex, namely in the left inferior frontal gyrus, suggesting that the delta network impairment in dyslexics might involve both hemispheres. In any case, the youngest participants of these studies had received at least an average of five years of formal reading instruction. Our participants, by contrast, were very beginning readers (one school year of reading instruction). If, as suggested by previous studies, reading instruction affects oscillatory activity (De Vos et al., 2017), it is logical to think that older participants' oscillatory responses will change due to the years of reading experience. Overall, as already discussed in Experiment 1, the lateralization of the coherence to speech phenomenon does not seem to follow a simple developmental trajectory, reason for which we also believe that hemispheric contribution to reading achievement might be more complex than suggested. The larger contribution of left hemisphere coherence at the delta band as compared to the right hemisphere in very beginning readers at T3 (if statistically proven) could signal the intense mobilization of the left-hemisphere reading network at very early stages of reading acquisition (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Dehaene, 2009). Nevertheless, these hypotheses should be taken with caution due to the weak statistical result, and further studies testing specifically the functional role of inter-hemispheric differences in coherence are needed to shed light into this issue.

Although coherence to speech at the theta band (4-8 Hz) has been related to reading skills (Abrams et al., 2009), we did not find any significant coherence to speech in this range (Experiment 1), and hence could not test this relation. It is nevertheless important to note a methodological difference between our and the previous study, namely that they found the relation between theta coherence and reading only when the speech was compressed (they found no relation for conversational or clear speech), whereas our speech signal was not manipulated. Similarly, we found no coherence to natural speech in the gamma range, reason for which previous results in dyslexic adults showing a relation between high-frequency oscillatory activity and reading skills could neither be replicated (Lehongre et al., 2013). This is not surprising, given that synchronised high-frequency oscillatory is normally found with power measures (e.g. Gross et al., 2013) and we used phase coherence measures. In any case, our developmental results for the coherence to speech in the delta band are in line with theories that assign right-hemispheric synchronization for the slow (prosodic) components of speech a fundamental role for the acquisition of adequate phonological skills and reading (Goswami, 2011; Lallier et al., 2018, 2017). By contrast, they do not support theories that claim for an *exclusive* high-frequency oscillatory deficit in relation to reading disorders, since they suggest that reading variance would not necessarily be captured by activity in low-frequency bands (Lehongre et al., 2011, 2013) and at least in our sample and with our measures, they do.

To our knowledge, this is the first study reporting a relation between reading achievement and coherence to natural speech in typically developing children. Indeed, as for the last time they were tested, none of our children was at risk of developing dyslexia or any other speech pathology, and none of the scores in the reading tasks deviated excessively from the mean of the sample (range in *z*-scores: from -1.22 to 1.96). According to our data, the brain-to-speech coherence measure was even able to capture longitudinal subtle reading variance in a typical (small) sample, where variability is reduced as compared to pathological populations.

Nevertheless, at least with our materials, analyses and sample, the delta rhythms-reading relation was not as straightforward as expected, since we did not find any significant relation between reading and coherence to the non-linguistic signals modulated at the delta (2 Hz) rate. This result is in principle at odds with transversal studies that found reduced delta (J. A.

Hämäläinen et al., 2012) phase synchronised activity in (older) dyslexic readers using very similar stimuli. Although the absence of results in this sense could be due to reduced statistical power, we did find significant correlations between reading and our coherence to speech measure with a very similar sample size, reason for which we believe that our mixed results could have their origin in the differences between our stimuli. The natural speech and the AM signals differ mainly in two aspects: the temporal predictability of their envelope and the presence/absence of linguistic information. Regarding the first aspect, it is possible that temporal processing of the (less rhythmic) envelope of speech is a more subtle measure to capture reading variance in typical readers as opposed to perfectly rhythmic stimulation. Reading variance in pathological populations is large and their deficits in oscillatory responses might already be visible with tasks testing perfectly rhythmic temporal processing such as AM signals. By contrast, the contribution of oscillatory responses to normal (and hence less variable) reading skills might be captured only in more challenging conditions, i.e. with stimulation whose temporal structure is not entirely predictable (see Power et al., 2013 for a similar argument). Concerning the second aspect, the natural speech and the AM signals also differ in linguistic nature, such that, as opposed to the non-linguistic AMs, natural speech is a signal provided of verbal (phonological) information. In consequence, it is possible that the natural speech signal triggered delta-band activity related to higher linguistic processes. Indeed, delta band activity has been shown to reflect not only acoustic parsing of the signal, but also higher-order processes related to, for example, syntactic parsing (Ding, Melloni, Zhang, Tian, & Poeppel, 2016; Meyer, Henry, Gaston, Schmuck, & Friederici, 2016). The prominent role of the delta band for specifically linguistic processes is also supported by, to our knowledge, the only research work that has directly compared coherence to natural speech and coherence to AM signals using MEG (Molinaro & Lizarazu, 2018). Although the authors focused their comparison on brain sources, at the sensor level they found larger coherence to natural speech at the delta band (1-2 Hz) as compared to 2-Hz AM signals in right temporal and in left inferior frontal sensors. Supported by several experiments, the authors argued that delta coherence to speech signals reflects higher processing specifically related to language, while the theta band would code for general acoustic information. Unfortunately, our paradigms do not allow disentangling between these two aspects (temporal structure and nature of the stimulus). To do so, it would be necessary to compare natural speech to an equally temporally rich signal, but deprived of verbal information (e.g. vocoded speech), and test their separate contribution to reading achievement. Such a paradigm would allow testing if the delta rhythms-reading relation is *purely acoustic* (i.e. derived exclusively from neural sensitivity to the temporal structure of the stimulus), or mediated by linguistic content. In any case, regardless the origin of the difference, delta coherence to the AM signals did not correlate with delta coherence to natural speech in our own sample, suggesting that this different type of stimulation might not be as comparable as previously suggested, at least in terms of brain coherent oscillatory activity. Importantly, this gives a new perspective into the study of language through non-verbal manipulated signals and suggests caution when drawing *linguistic* conclusions when using non-linguistic stimuli. Our results suggest that natural language, besides being an evidently more ecological stimulus, might be a more adequate measure to capture the contribution of slow oscillatory activity in the early stages of typical reading acquisition.

We did not find any significant relation between coherent activity to theta-band AMs and reading achievement, failing hence to replicate previous studies (Lizarazu et al., 2015). Nevertheless, note that the evidence was already mixed, such that the longitudinal study by De Vos et al. (2017) testing pre-reading children also failed to find any contribution of theta oscillatory activity for reading development using power measures. Finally, since coherence to the 30-Hz AM was not significant at any testing time in our sample, we could not extend results on the contribution of oscillatory activity at high-frequencies for reading development in terms of power (De Vos et al. 2017) to the phase domain. Again, this is the first study testing very young typically developing children prior and after reading acquisition with coherence measures and the nature of our results is therefore mainly exploratory. Further studies controlling exhaustively the stimuli's temporal and linguistic nature are needed to draw definite conclusions on the contribution of coherence to the different frequency bands to reading development.

Conclusions of Experiment 3

In this Experiment, we showed that brain-to-speech coherence within the delta frequency band in right temporal sites of the scalp prior to formal reading instruction predicted reading achievement one year later in our sample of typically developing children. Moreover, the longitudinal change in brain-to-speech coherence values from pre-reading to initial reading stages suggested that this measure could also a have a high potential for the prediction of children's reading achievement. By contrast, we did not find a relation between coherence to AM signals at the delta rate and reading achievement. This result points towards the fact that the relation between coherence at delta rhythms and reading might be mediated by the temporal structure of the stimulus and/or by higher order processes related to verbal processing. Our study suggests that non-manipulated ecological verbal signals might be a more appropriate stimulation as compared to non-verbal modulated signals when looking for the contribution of auditory brain oscillatory activity for reading acquisition, at least in small samples of typically developing participants.

4.4. Conclusions of Chapter 4

In this chapter we described the longitudinal trajectory of coherence to Natural speech (Experiment 1) and to amplitude-modulated (AM) signals at the prosodic, syllabic and phonemic rates (Experiment 2) and we tested their contribution to reading development (Experiment 3). We were able to highlight different trajectories of coherence as a function of the nature of the stimulation, such that coherence to speech was only present in the delta band (0.5 Hz) while coherence was significant both for the delta- (2 Hz) and theta- (4 Hz) AM signals. Overall, this evidence suggests that coherence to the slow components of speech might well be the mechanism through which the brain parses the linguistic signal since childhood (Giraud & Poeppel, 2012; Poeppel et al., 2008). Nevertheless, we did not always find the hemispheric bias for low-frequencies processing suggested by previous literature (Abrams et al., 2008; Bourguignon et al., 2013; J. A. Hämäläinen et al., 2012). With the exception of coherence to the 2-Hz AM signal at T2, which was more pronounced in the right hemisphere, we found no inter-hemispheric differences in coherence to speech or to the AM signals in any other testing time. This result suggests a complex developmental trajectory of cerebral asymmetries in coherence that will interact with age and linguistic experience. By contrast, we were not able to capture significant coherence to higher frequencies in any of the experiments, suggesting that this might increase with age and reading (phonological) experience (e.g. Lizarazu et al., 2015).

Regarding the contribution of oscillatory activity to reading, we only found significant results within the delta band and with our natural speech stimulus. In this context, our results revealed that delta-band coherence to speech in right temporal sites of the scalp in pre-reading stages (T2) correlated significantly with reading achievement in T3. This evidence is in line with theories assigning right-hemispheric coherence to the slow components of speech a causal role in the formation of appropriate phonological representations, and in turn of reading (Goswami, 2011; Goswami et al., 2014; Lallier et al., 2018, 2017). Although the result was statistically weak, we also found that the increase in delta coherence in electrode T8 during the period in which children received formal reading instruction correlated negatively with reading achievement. Based on a similar result previously reported in terms of power (De Vos et al., 2017), we concluded that this larger increase in oscillatory activity in children with poorer reading skills might signal compensatory mechanisms. In any case, in our experiment, only the delta-coherence to natural speech, which is provided with verbal information and whose amplitude envelope is not perfectly periodic, was able to capture the (reduced) reading variance of our typically developing children, while we failed to show that reading was significantly predicted by coherence to the AM signals at the delta band. These results suggest that the variable temporal structure and/or the verbal nature of natural speech might be at the roots of the contribution of delta-band entrainment to reading achievement, at least in young typically developing children. However, it is important to highlight that due to our reduced sample size, we cannot discard that future studies with more statistical power will be able to capture subtler contributions of oscillatory activity in response to non-linguistic stimulation to reading development.

Chapter 5: The contribution of behavioural rhythmic entrainment to reading development

In this chapter, our objective was to further test the contribution of rhythmic sensitivity at low-frequency bands to reading acquisition, but in this case at the behavioural level, with the goal of complementing the electrophysiological experiments presented in Chapter 4. To this aim, this chapter examines the relation between the development of behavioural rhythmic synchronization and other reading-related skills, to finally examine its contribution to reading achievement. Overall, in the following we will try to answer to our third research question, namely

- Research question 1: How does oscillatory activity in response to speech and to auditory stimuli modulated at rates relevant for speech perception develop during childhood? (Experiments 1 and 2, respectively)
- Research question 2: What is the contribution of brain oscillatory activity to reading acquisition? (Experiment 3)
- **Research question 3: What is the contribution of rhythmic behavioural skills to reading acquisition? (Experiment 4)**
- Research question 4: Can we use brain rhythms and behavioural rhythms as *equivalent* measures for the prediction of reading achievement? (Experiment 5)

5.1. Experiment 4: The value of behavioural synchronised rhythmic activity as a measure of reading readiness

5.1.1. Introduction

Reading readiness could be defined as the set of early (pre-reading) cognitive and behavioural skills that predispose a child to successfully acquire later reading (Whitehurst & Lonigan, 2001). Reading readiness has been extensively studied in the literature, and several pre-reading abilities have been causally (longitudinally) linked to reading. From these abilities, four in particular have received consistent support in the literature: phonological awareness, rapid automatized naming (RAN), letter name/sound knowledge (LNK) and phonological short-term memory (PSTM). First, reading acquisition seems to depend tightly on the child's phonological awareness, i.e. on the explicit awareness that speech is constituted by phonemes (individual speech sounds) and their combinations (Vellutino et al., 2004). Accordingly, impairments in phonological awareness have been consistently found to predict reading disabilities (Bowers & Swanson, 1991; Bradley & Bryant, 1978; Landerl et al., 2013; Ramus, Marshall, Rosen, & Van Der Lely, 2013; Snowling, 2001; Wagner et al., 1987). Second, one of the most powerful (and at the same time poorly understood) predictors of reading is the ability to rapidly name sequences of images (colours, numbers or simple drawings), which is typically measured through the RAN task (Bowers & Swanson, 1991; Parilla, Kirby, & Mcquarrie, 2004; Scarborough, 1998; Swanson, Trainin, Necoechea, & Hammill, 2003; van den Bos, Zijlstra, & Spelberg, 2002; Wolf, Bally, & Morris, 1986; Wolf, 1991). The knowledge of the letters of the alphabet (or their sound) prior to reading acquisition would constitute the third classical predictor, since it has been consistently linked to future reading skills (Burgess & Lonigan, 1998; Byrne & Fielding-Barnsley, 1990; Stevenson & Newman, 1986; Stuart & Coltheart, 1988), sometimes even above phonological awareness (Evans, Bell, Shaw, Moretti, & Page, 2006; Pennington & Lefly, 2001). Last but not least, phonological short-term memory (PSTM), measured classically through word and non-word repetition tasks, has also been linked to the quality of children's phonological buffer (Baddeley, Gathercole, & Papagno, 1998), which contributes essentially to the acquisition of reading (Jorm, 1979; Mann & Liberman, 1984; Muter & Snowling, 1998; cf. McDougall, Hulme, Ellis, & Monk, 1994; Scarborough, 1998).

In spite of the huge step forward that finding these (verbal) predictors of reading has meant for the literature on reading disorders, a fundamental question steps in, namely what is the origin of the inter-individual differences in such abilities. In the endeavour to answer this question, scientists have looked for the cognitive predecessors of reading predictors, and most intensely in the field of speech perception. Indeed, in Western societies, children are exposed to spoken language at least during five or six years before they formally learn the systematic principles that govern reading and writing, i.e. the arbitrary mapping between speech sounds (phonemes) and their written form (graphemes). From this perspective, the acquisition of reading should be *founded on*, or at least supported by, children's previous experience with the speech signal.

As highlighted throughout this doctoral thesis, the speech signal is characterised by amplitude changes at different time scales that generate what we know as the *speech rhythms*. Importantly, the most (perceptually) salient rhythms of speech occur at low temporal rates (<8 Hz; Houtgast & Steeneken, 1985) and reflect prosody and the succession of syllabic chains (Ghitza & Greenberg, 2009; Goswami, 2011). Even before being able to speak, human babies use the speech rhythm for a wide variety of language-related tasks, such as discriminating between languages (Ramus et al., 2000) or discriminating rhythmic patterns of strong and weak syllables (Jusczyk & Thompson, 1978), which would help them developing sensitivity to the typical stress patterns of their native language and hence provide them with a basis to detect syllable boundaries and segment the continuous speech signal into its constituents (Cutler & Mehler, 1993; Morgan & Saffran, 1995).

The fundamental role of the speech rhythm for segmenting the linguistic signal from infancy has given rise to theories claiming that sensitivity to the rhythm of speech would be core for the development of proper representations of speech individual sounds (phoneme awareness), and in turn for reading development (Goswami, 2011; Goswami et al., 2002; Lallier et al., 2018, 2017). Supporting this hypothesis, dyslexic children and adults have been found to perform poorly as compared to control readers in a wide variety of rhythm perception and production tasks. Here it is important to note that rhythm *perception* has been profusely tested with rhythm *production* tasks based on the assumption that a single timing mechanism underlies both of them (Drake, Jones, & Baruch, 2000; Fraisse, 1963; Ivry & Hazeltine, 1995; Keele, Pokorny, Corcos, & Ivry, 1985; Treisman, Faulkner, & Naish, 1992). Regarding rhythm perception, for example, dyslexic children and adults are less sensitive to amplitude envelope rise time, i.e. the amplitude peaks in the signal that normally signal the onset of syllables (Goswami et al., 2002; Pasquini, Corriveau, & Goswami, 2007). Reduced sensitivity to the speech rhythm has been found in children at familial risk of dyslexia (de Bree, Wijnen, & Zonneveld, 2006), in dyslexic children (Huss et al., 2011) and in dyslexic adults (Thomson et al., 2006). Concerning rhythmic production, which is usually measured by tasks in which participants have to tap in synchrony with an external periodic rhythm or tap after a whole (variable or not) rhythm is presented, multiple studies have reported a positive correlation between rhythmic abilities and reading skills in transversal studies (Corriveau et al., 2010; Corriveau & Goswami, 2009; Dellatolas, Watier, Le Normand, Lubart, & Chevrie-Muller, 2009; Flaugnacco et al., 2014; Overy, Nicolson, Fawcett, & Clarke, 2003; Thomson et al., 2006; Thomson & Goswami, 2008; Tierney & Kraus, 2013b).

Importantly, all the studies reviewed above assessed participants who had failed or not to develop appropriate reading skills, but who had in the end received reading instruction. Therefore, they do not allow us discarding the presence of mutual (and not unidirectional/causal) contributions between reading acquisition and rhythm sensitivity. More appropriate evidence in this direction comes from longitudinal studies that established a relation between rhythmic sensitivity prior to reading acquisition and future reading, and from transversal studies reporting a tight relation between rhythmic sensitivity and other classical reading predictors in pre-readers (Anvari, Trainor, Woodside, & Levy, 2002; Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014; David, Wade-Woolley, Kirby, & Smithrim, 2007; Holliman, Wood, & Sheehy, 2010; Lundetræ & Thomson, 2017; Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2013). Regarding the relation between rhythm skills and classical reading predictors, Moritz et al., (2013) showed that the ability of pre-reading kindergartners to copy a rhythm (with variable or periodic tempo) was positively correlated with their performance in a phoneme segmentation task transversally and at the end of Grade 2. Nevertheless, tasks that involve copying after stimulus presentation require memory and motor repetition, while online rhythm sensitivity might be best reflected in tasks that require synchronous rhythmic entrainment, such as tapping to a beat tasks (Lundetræ & Thomson, 2017). In this line, the ability of five-year old pre-readers to tap in synchrony to external periodic rhythms (at rates of 1.67 and 2.5 Hz) has been shown to correlate significantly with phonological awareness, phonological short-term memory and RAN (Carr et al., 2014). Overall, this evidence supports the idea that rhythmic abilities could be a good index of reading readiness in pre-schoolers. Nevertheless, these previous studies testing the relation between rhythmic skills and reading readiness have mostly focused on *phonological* reading predictors, i.e. on phonological awareness, phonological short-term memory and RAN (Moritz et al., 2013; Carr et al., 2014), whereas no study has specifically assessed the relation between rhythmic abilities and a more orthographic predictor such as LNK. As mentioned above, LNK is a powerful reading predictor that in some cases has been suggested to predict reading above and beyond phonological processes (Evans et al., 2006; Pennington & Lefly, 2001). Given the relation between orthographic predictors (LNK), phonological predictors (RAN/phonological awareness) and reading on the one hand (see Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004 for a review), and the relation between rhythmic abilities and phonological predictors on the other hand (Moritz et al., 2013; Carr et al., 2014), it is sensible to hypothesise that rhythmic abilities will also be related to children's behavioural orthographic sensitivity before formal reading instruction.

Finally rhythmic skills at pre-reading stages have also been related to future reading performance (Dellatolas et al., 2009; Holliman et al., 2010; Lundetræ & Thomson, 2017). Longitudinally, sensitivity to the speech rhythm in pre-reading children has been related to their reading skills one year later (Holliman et al., 2010). In production studies, a rhythm-copying task at kindergarten was reported to contribute significantly to reading performance in Grade 2 (Dellatolas et al., 2009). However, as mentioned above, this task might not be optimal to measure online rhythm sensitivity. Only one study to our knowledge has examined the developmental relation between rhythmic skills and reading with a tapping to a beat task (Lundetræ & Thomson, 2017). This study showed that, along with common factors such as short-term memory, LNK and phonological awareness, the ability to tap to a beat at a 1.5 Hz rate at the beginning of Grade 1 (prior to reading instruction) predicted poor reading at the end of

Grade 1 (Lundetræ & Thomson, 2017). Here it is important to note that, by itself, the tapping to a beat task at the beginning of Grade 1 was only a marginally significant predictor of poor reading one year later. By contrast, adding the task to a logistic regression model that already included LNK, phonological awareness, RAN and familial risk for dyslexia improved significantly the model's power to classify poor readers (from 29.7% to 35.9%). This suggests that the contribution of rhythmic skills to reading achievement was not independent, but that it interacted with the rest of predictors, supporting the multi-factorial nature of literacy emergence (Menghini et al., 2010; Peyrin et al., 2012). In any case, this study was targeted at predicting poor reading, while no study in the literature has tested the contribution of rhythmic skills to typical reading development. Nevertheless, the relation between rhythm sensitivity and reading has also been shown transversally in typically developing children (e.g. Holliman, Wood, & Sheehy, 2008; Wood, 2006) and indeed, if rhythm sensitivity is essential for the development of reading, it should be associated with both impaired and typical reading (Wood, Wade-Woolley, & Holliman, 2009).

This study

The main aims of the current experiment were to test the relation between early rhythmic sensitivity at low (delta) frequencies and other classical reading predictors, and to examine its contribution to later reading achievement in typically developing children. To those aims, we tested a group of children along three testing times: twice before reading was formally introduced in the school curriculum (T1 and T2) and a third time after they had received one school year of reading instruction (T3). At T1 and T2, children completed a battery of behavioural tasks assessing classical reading predictors (LNK, phonological awareness, phonological short-term memory and RAN) and a rhythm task consisting in tapping in synchrony to a beat at 1.67 Hz. At T3, the children completed the same battery of behavioural tasks (plus a working memory task) and their reading performance was assessed.

Hypotheses

Based on previous studies that have reported a tight relation between rhythmic skills and reading (phonological) predictors such as the RAN, phonological awareness and phonological short-term memory (Moritz et al., 2013; Carr et al., 2014), we expected that our rhythmic synchronization task would be tightly related to these tasks at pre-reading stages (T1 and T2). We also expected rhythmic abilities to correlate with a more orthographical predictor such as LNK, due to the tight relation between this and the phonological predictors mentioned above (Schatschneider et al., 2004). Lastly, we expected pre-reading rhythmic synchronization skills to contribute to future reading achievement (Lundetræ & Thomson, 2017) also in a sample of typically developing children.

5.1.2. Materials and methods

5.1.2.1. Participants

Forty-two children attended the behavioural session at T1 (age *M* = 5.09 years; *SD* = .31; 22 males). Twenty-nine of the children were characterised as Basque dominant and 13, as Spanish dominant. Five of the children were left-handers.

The sample size for the behavioural battery was of 38 children (age *M* = 5.88 years; *SD* = .34; 19 males) at T2. Twenty-six and 12 of the children were defined as Basque or Spanish dominant, respectively. Five of the children were left-handers.

Finally, 33 children (age *M* = 6.98 years; *SD* = .32; 18 males) came back for testing at T3. Twenty-two and 11 children were characterised as Basque or Spanish dominant, respectively. Four of the children were left-handers.

Note that the fact that children attended the behavioural session did not involve that they completed all tasks. The corresponding sample size for each analysis is provided in the *Results* section.

5.1.2.2. Stimuli and procedure

The stimuli and procedure for the reading tasks have already been presented in section 3.2.2.1.2 of Chapter 3. Accordingly, only the stimuli and procedure for the battery measuring reading predictors will be described in this section. See Table 3.2 (Chapter 3) for a schematic representation of the tasks that the children completed across the testing times.

5.1.2.2.1. Rapid automatized naming (RAN), colours subset (T1, T2 and T3)

The RAN task has been extensively used as valid predictor of reading skills, and speed scores in particular have been shown to correlate with future reading abilities (see Norton & Wolf, 2012 for a review). In our case, stimuli consisted of six different colours and were presented digitally in a computer screen. First, we ensured that children knew the name of the six colours involved in the task (black, brown, yellow, red, blue and green). After this, a matrix of nine columns and four rows (total of 36 items) appeared in the screen, and children were asked to name the colours from left to right and from top to bottom as fast and with as few mistakes as possible. Number of errors and time were recorded. This task took approximately five minutes.

5.1.2.2.2. Pseudoword repetition (T1, T2 and T3)

This task has been extensively used to measure phonological short-term memory and its contribution to reading skills (Jorm, 1979; Mann & Liberman, 1984; Muter & Snowling, 1998). Stimuli were presented through headphones at an SPL of 80 dB. Stimuli consisted in a total of 28 items that complied with Basque phonotactics and the child was instructed to repeat the corresponding item immediately after he/she heard it. Stimuli consisted in items differing in length: 8 two-syllable items, 8 three-syllable items, 6 four-syllable items, and 6 five-syllable items. Seventy per cent of the stimuli were formed by syllables whose phonemic structure followed the consonant-vowel pattern. For the thirty per cent of remaining stimuli, one syllable contained a consonant cluster (three letters; e.g. /pra/). In order to adapt the difficulty of the task to the children’s age, stimuli’s length and structure was slightly changed in T2 and T3. For these testing times, stimuli length was as follows: 7 two-syllable items, 7 three-syllable items, 8 four-syllable items and 8 five-syllable items. Within them, 50% contained a syllable cluster, while the syllables of the remaining 50% followed a consonant-vowel structure at the phonemic level. Items were changed from T2 and T3 to avoid (not likely) repetition effects across the years. In each testing time, two practice items were presented before the task started to ensure that the children understood the task. This task took approx. five minutes. Total time for the repetition of the whole list and errors were recorded by the experimenter. To allow longitudinal comparison, a measure of efficiency per minute was calculated as follows:

$$\text{Pseudoword efficiency} = \frac{\text{Total number of correct pseudowords}}{\text{Total time}} * 60$$

5.1.2.2.3. Letter name knowledge (T1, T2 and T3)

The knowledge of the letters name/sounds has been shown to predict reliably children's reading skills (Burgess & Lonigan, 1998; Byrne & Fielding-Barnsley, 1990; Evans et al., 2006). The letters of the Basque alphabet (n = 27) were presented in capital case and one by one in a random order. The child's task was to name the letter. The experimenter recorded accuracy scores (maximum score of 27). This task was completed in approx. three minutes.

5.1.2.2.4. Phoneme deletion/elision (T1, T2 and T3)

This task has been extensively used to measure phonological awareness in young children (e.g. Stanovich, Cunningham, & Cramer, 1984). Stimuli consisted of a total of 16 pseudowords and were presented one at a time through headphones at 80 dB SPL. Immediately after presentation, children were asked to recall them, but omitting the first phoneme of the pseudoword (phoneme deletion) for half of the items (eight) and the first phoneme of the pseudoword's second syllable (phoneme elision) for the remaining half. For each subtask, stimuli consisted of eight by-syllabic items that were presented in a randomised order. Within the deletion task, half of the items (four) consisted of two syllables with a consonant-vowel structure (CV; e.g. /timu/; correct response: /imu/). The remaining half of the items had a consonant-consonant-vowel (CCV) structure in the first syllable and a simple CV structure in the second (e.g. /bluno/, correct response: /luno/). The structure of the stimuli for the elision subtask was identical to the deletion subtask (i.e. four CV-CV items and four CCV-CV items). Children now had to omit the first phoneme of the second syllable (e.g. /bupa/; correct response: /bua/) and consequently, they never had to *break down* a consonant cluster (i.e. /flope/; correct response: /floe/). This was done in order to decrease the task complexity due to our participants' young age. The number of correct responses was recorded (maximum of 16).

5.1.2.2.5. Digit span backward (T3)

The contribution of working memory to reading skills has been extensively highlighted in the literature (e.g. Cain, Oakhill, & Bryant, 2004; Carretti, Borella, Cornoldi, & De Beni, 2009). Therefore, at T3 (when children were old enough to complete this type of task reliably) we introduced a working memory measure: the Digit span backward task from the WISC-IV (Wechsler, 2003). The child listened one by one to lists of digits ranging from numbers 1 to 9 recorded by a male native Basque speaker and was asked to recall the whole corresponding list in order immediately after. The task consisted of eight trials with two lists each (total of 16 lists). Lists ranged from two to eight items (digits), such that the lists of the first and the second trials consisted of two items, the lists of the third trial of three items, the lists of the fourth trial of four items, etc., until reaching the eighth trial, whose lists consisted of eight items. The experimenter stopped the task when children failed to answer correctly to the two lists of a trial. Direct scores (i.e. total number of lists correctly produced) was recorded.

5.1.2.2.6. Beat synchronization (T1, T2 and T3)

To assess the rhythmic skills of the children, we adapted a task that has been previously shown to correlate with other reading predictors in pre-readers (Carr et al., 2014). The task was originally proposed by Kirschner and Tomasello (2009) as the best available task to measure children's rhythmic skills in social situations. In this task, the child is asked to tap to a beat in synchrony with the experimenter. This situation, due to the social interaction with another human being, generates a special motivation for synchronised movement that is absent when tapping to a recorded rhythm (Kirschner & Tomasello, 2009). In our case, the experimenter produced a rhythmic drum beat and children were asked to "synchronise" to this rhythm, i.e. to tap at the tempo set by the experimenter. Children were asked to tap with their dominant hand, since significant group differences when tapping to a beat with the dominant *versus* the non-dominant hand have been previously reported in the literature (Nozaradan, Zerouali, Peretz, & Mouraux, 2015). Before the task, the experimenter was trained to produce the rhythmic pattern as accurately as possible, so that the mean *SD* of her inter-drum intervals was below 25 ms. The task consisted of two trials at 1.67 Hz (606 ms ISI; duration of 20 seconds; total 50 beats). The experimenter and the child produced the drum beats separately in a peripheral drumming pad. Input was recorded via a custom-script created in *Python*.

5.1.2.3. Data analysis

5.1.2.3.1. Drumming consistency: Circular statistics

Data analysis of the BSynch task was based on circular statistics (Fisher, 1993). Circular statistics are intended to assess the level of synchronization to the pace of an external beat (see Kirchner & Tomasello, 2009 for a full justification for the use of this type of statistics with children data). We recorded both onset and offset movements, but for the purpose of this study only onsets were analysed. Data analysis consisted of the following steps: i) Drum hits were assigned a point in a circular scale, with the stimulus beat aligned at 0º. Every beat was defined by an angle in degrees or phase, i.e. the result of subtracting the onset time from the onset of the stimulus closest in time. In this way, it is possible to measure the degree of synchronization independently of its attribution to the preceding or following stimulus drum hit, i.e. instead of using traditional linear statistics, a measure of phase consistency is created; ii) thereafter, the result was divided by the ISI and multiplied by 360; iii) lastly, all vectors are summed and divided by the number of hits generated, which renders a mean vector *R*. The mean vector *R* gives information about two parameters: the vector's mean direction *h*, which can be used as a measure of the child's phase preference, and the vector's mean length. The latter provides a measure of the phase consistency of the produced drum hits with regard to the stimulus. Its value ranges between 0 (no phase consistency) and 1 (perfect phase consistency). For the purpose of this experiment, we only analysed the vector *R*'s mean length.

We performed statistical tests on the mean length of vector *R* via Rayleigh's test using the function *circ_rtest*() available in Matlab's package *CircStat* (Berens, 2009). This function renders two values per subject: the *z*-transformed mean length of vector *R* and its associated *p*-value.

According to the procedure explained in section 3.2.3.1 (*Outlier treatment*) of Chapter 3, the children's *z*-values were screened to detect the presence of longitudinal outliers (i.e. children whose performance decreased inexplicably along the testing times). We did so because behavioural rhythmic entrainment to an external rhythm tends to improve with age (Colling et al., 2017; Drake et al., 2000; McAuley, Jones, Holub, Johnston, & Miller, 2006) and due to the dynamic nature of the task, we estimated that when such a detriment was present, the probability of measurement error, children's fatigue, lack of motivation and/or attention was high. To establish an objective numerical criterion for data exclusion, we considered that the detriment in performance was too prominent when children's score was 3 *z*-values less than on the previous testing time(s). We further confirmed that the children were outliers performing test-retest reliability analyses of the task with and without the scores of these children. When the reliability of the task was notably affected by these observations, they were not used in further analyses.

The *p*-value rendered by the Rayleigh's test can be used as a measure to group the participants as a function of their degree of phase synchronization with the external beat, such that *p*-values smaller than the selected statistical threshold signal significant phase synchronization, whereas values that surpass this threshold signal absence of synchronization. We established our alpha level at .05, and hence considered children to be Synchronisers (Synch) when their *p*-value for the Rayleigh's test was less than .05, and Non-synchronisers (Non-synch) when their *p*-value in the test surpassed the .05 threshold (for a similar procedure see Kirschner & Tomasello, 2009; Carr et al., 2014).

5.1.2.3.2. Relation between the BSynch task and the remaining tasks

We tested the transversal and longitudinal relation between the BSynch task and

i) the rest of reading predictors across testing times;
ii) the reading scores at T3.

The main aim of our analyses was to test if children who performed better in the BSynch task showed also better performance in the rest of tasks measuring reading predictors and reading. To this goal, we first performed partial Spearman correlations between the tasks in order to detect meaningful inter-relations between them and reduce the number of comparisons for later analysis. When the coefficient of the specific pair-wise correlation was equal or above .30 (i.e. at least low strength; Hinkle, Wiersma, & Jurs, 2003) and/or its associated *p*-value before FDR correction was equal or below .10 (one-tailed), we further explored it using median comparison methods.

Median comparisons between the Synch and Non-synch groups were first performed through Mann-Whitney tests, in which age and IQ were not controlled for, and later confirmed through a second analysis including these covariates (non-parametric ANCOVAs using *R*'s function *sm.ancova()* from package *sm*).

5.1.3. Results

The main aim of this Experiment was to explore the relation between rhythmic ability and the remaining predictors and reading measures. Accordingly, we restricted our main analyses to the inter-relations involving the BSynch task. Nevertheless, section A4 of the Appendix presents comprehensive descriptive statistics (Table A4.1) and transversal and longitudinal partial correlations among our complete set of tasks (Tables from A4.2 to A4.4).

Importantly, the letter name knowledge (LNK) task was not included in the analyses in T3 due to ceiling effects. Regarding the Phoneme deletion/elision task measuring phonological awareness, the task appeared to be too difficult for the children at T1 and T2 (floor effects), and hence it was only included in the analyses of T3.

This section is divided in several subsections according to the procedure explained in the statistical analysis section. The introductory section presents descriptive statistics and outlier removal for the BSynch task, while section 5.1.3.1 examines its test-retest reliability. Thereafter, we explore the relation between the BSynch task and: i) the rest of classical reading predictors across the three testing times (section 5.1.3.2); and ii) reading outcome at T3 (5.1.3.3).

Descriptive statistics and longitudinal outlier removal

Inspection of the data from the longitudinal perspective indicated that the performance of several children in the BSynch task at T2 and T3 had decreased notably (in more than 3 *z*-values; see section 5.1.2.3.1) as compared to the previous testing time(s). This was the case of seven children in T2 and of two children in T3 (see observations marked with an asterisk in Table 5.1.1). Moreover, we confirmed that the score of these children affected the test-retest reliability of the task, such that the task did not correlate with itself across the years when these children were included in the analyses (all ρs < .20; all *p*s > .10) while reliability was higher when they were not (see section 5.1.3.1 below).

Table 5.1.1. The top part of the table shows individual scores in the BSynch task across the testing phases (*z* and *p* values resulting from the Rayleigh's test, and Group depending on the *p* value). The bottom part of the table shows descriptive group statistics and information about the data distribution. Group statistics for the data prior to outlier removal are presented in brackets.

	T1			T2			T3		
Subj	*z*	*p*	**Group**	*z*	*p*	**Group**	*z*	*p*	**Group**
1	1.59	.21	NS	1.71	.18	NS	13.08	<.01	S
2	1.87	.15	NS	3.42	.03	S	3.32	.03	S
3	15.65	<.01	S	1.90*	-	-	2.68	.07	NS
4	.09	.91	NS	1.95	.14	NS	1.80	.17	NS
5	3.39	.03	S	2.12	.12	NS	-	-	-
6	2.94	.05	S	14.64	<.01	S	.94*	-	-
7	1.81	.16	NS	2.22	.11	NS	3.66	.03	S
8	.53	.59	NS	-	-	-	-	-	-
9	.78	.46	NS	3.48	.03	S	13.44	<.01	S
10	8.43	<.01	S	1.23*	-	-	2.67	.07	NS
11	0	1.00	NS	-	-	-	1.15	.32	NS
12	5.54	<.01	S	.66*	-	-	-	-	-
13	.62	.54	NS	21.57	<.01	S	16.61	<.01	S
14	.49	.61	NS	1.73	.18	NS	-	-	-
15	1.67	.19	NS	1.06	.35	NS	1.31	<.01	S
16	.17	.84	NS	9.87	<.01	S	.36*	-	-
17	1.87	.15	NS	3.01	.05	S	24.60	<.01	S
18	24.43	<.01	S	-	-	-	-	-	-
19	.38	.69	NS	.27	.77	NS	-	-	-
20	1.81	.16	NS	2.7	.07	NS	3.10	.04	S
21	3.62	.03	S	2.08	.12	NS	5.59	<.01	S
22	.87	.42	NS	2.72	.07	NS	.86	.42	NS
23	1.39	.25	NS	.25	.78	NS	3.97	.02	S
24	5.90	<.01	S	.63*	-	-	3.59	.03	S
25	4.87	.01	S	21.07	<.01	S	16.68	<.01	S
26	.24	.79	NS	.44	.65	NS	24.89	<.01	S
27	4.49	.01	S	15.61	<.01	S	4.55	<.01	S

28	.72	.49	NS	2.81	.06	NS	11.37	<.01	S
29	2.45	.09	NS	.38	.69	NS	2.95	.05	S
30	.79	.45	NS	2.16	.11	NS	-	-	-
31	5.10	.01	S	1.68*	-	-	5.04	.01	S
32	2.01	.13	NS	6.69	<.01	S	22.55	<.01	S
33	4.74	.01	S	-	-	-	-	-	-
34	1.38	.25	NS	.42	.66	NS	4.22	.01	S
35	2.09	.12	NS	-	-	-	-	-	-
36	.18	.84	NS	2.2	.11	NS	.07	.93	NS
37	9.12	<.01	S	.87*	-	-	1.52	.22	NS
38	3.42	.03	S	8.23	<.01	S	38.76	<.01	S
39	1.44	<.01	S	1.49*	-	-	3.50	.03	S
40	.23	.80	NS	-	-	-	.51	.61	NS
41	2.06	.13	NS	7.58	<.01	S	4.88	.01	S
42	1.74	.18	NS	5.42	<.01	S	29.79	<.01	S
Group statistics									
n	42			(36) 29			(33) 31		
M	3.38			(4.34) 5.10			(9.67) 1.25		
SD	4.62			(5.37) 5.98			(11.22)11.34		
Mdn	1.84			(2.14) 2.70			(3.97) 4.22		
skew	2.76			(1.91) 1.59			(1.37) 1.29		
kurtosis	8.7			(2.68) 1.42			(.81) .58		
SE	.71			(.93) 1.11			(1.95) 2.04		

NS = Non-synchroniser; S = Synchroniser; Subj = Subject
Longitudinal outliers are marked with an asterisk (*).

5.1.3.1. Test-retest analysis of the BSynch measure

Partial Spearman correlations of the BSynch measure across testing times after longitudinal outlier removal showed that it correlated significantly in consecutive testing times (T1-T2 and T2-T3), but not between T1 and T3 (see Table 5.1.2).

Table 5.1.2. Test-retest analysis of the BSynch measure

	T2			**T3**		
	n	***ρ***	***p***	**n**	***ρ***	***p***
T1	.29	.41	.03*	31	.14	.45
T2		--		23	.47	.02*

5.1.3.2. Relation between the BSynch measure and classical reading predictors

This section explores the transversal and longitudinal relation of the BSynch tasks with the remaining reading predictors in two steps, as explained in section 5.1.2.3.2 of the current chapter. First, the results of the correlations between the BSynch task and the reading predictors are presented (section 5.1.3.2.1). Based on the results of this first analysis, the children's performance is tested with median-comparison methods (5.1.3.2.2).

5.1.3.2.1. Partial correlation analyses

5.1.3.2.1.1. The BSynch task at T1

Complete results of the transversal and longitudinal correlation analyses between the BSynch task at T1 and the remaining the tasks at T1, T2 and T3 can be seen in Table 5.1.3. As shown in this table, the BSynch task at T1 correlated significantly with the LNK and with the Pseudoword repetition tasks at T1 (see left panel of Figure 5.1.1), such that children with better rhythmic skills showed better phonological short-term memory and better knowledge of the letters of the alphabet. Longitudinally, the BSynch measure at T1 was again correlated with LNK and with Pseudoword repetition at T2 (see right panel of Figure 5.1.1). Finally, none of the reading predictors at T3 correlated with the BSynch task at T1, although the correlation with Pseudoword repetition almost approached significance.

Table 5.1.3. Spearman correlations between the BSynch task at T1 and the remaining reading predictors across testing times

		BSynch T1			
		n	***ρ***	***p***	***FDR***
T1	**RAN**	39	-.14	.38	.38
	PWRep	41	.33	.03*	.05*
	LNK	41	.47	.002*	.006*
T2	**RAN**	34	-.26	.14	.14
	PWRep	36	.36	.03*	.09
	LNK	36	.32	.06·	.09
T3	**RAN**	31	-.02	.92	.98

PWRep	33	.29	.10	.40
PhDel	31	-.01	.97	.98
DSB	32	.004	.98	.98

DSB = Digit span backward; PWRep = Pseudoword repetition; PhDel = Phoneme deletion/elision

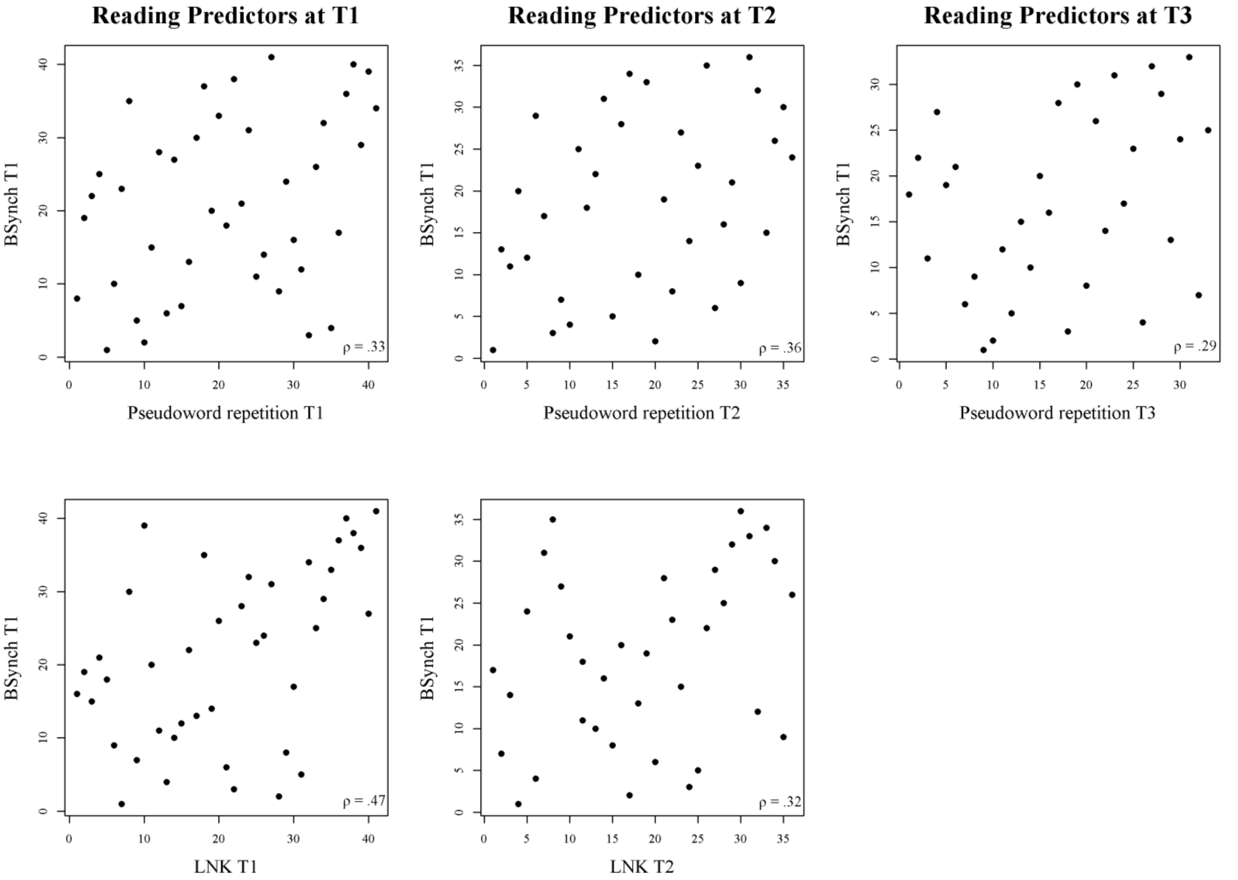

Figure 5.1.1. Partial Spearman correlations between the BSynch task at T1 and reading predictors at T1 (left panel), T2 (central panel) and T3 (right panel)

5.1.3.2.1.2. The BSynch task at T2

The complete results for these correlations can be seen in Table 5.1.4. Within T2, the BSynch task correlated positively with LNK, meaning that children with better rhythmic skills had better knowledge of the letters of the alphabet (see left panel of Figure 5.1.2). A negative correlation between the RAN task and the BSynch task was also found, such that children with better rhythmic abilities were the ones who took less time in completing the RAN task (see right panel of Figure 5.1.2).

Table 5.1.4. Spearman correlations between the BSynch task at T1 and the remaining reading predictors across testing times

		BSynch T2			
		n	***ρ***	***p***	***FDR***
T2	**RAN**	26	-.36	.03	.05*
	PWRep	27	.14	.48	.48
	LNK	27	.55	<.001*	.001*
T3	**RAN**	24	-.28	.19	.35
	PWRep	25	.26	.21	-35
	PhDel	23	.25	.26	.35
	DSB	24	.15	.48	.48-

DSB = Digit span backward; PWRep = Pseudoword repetition; PhDel = Phoneme deletion/elision

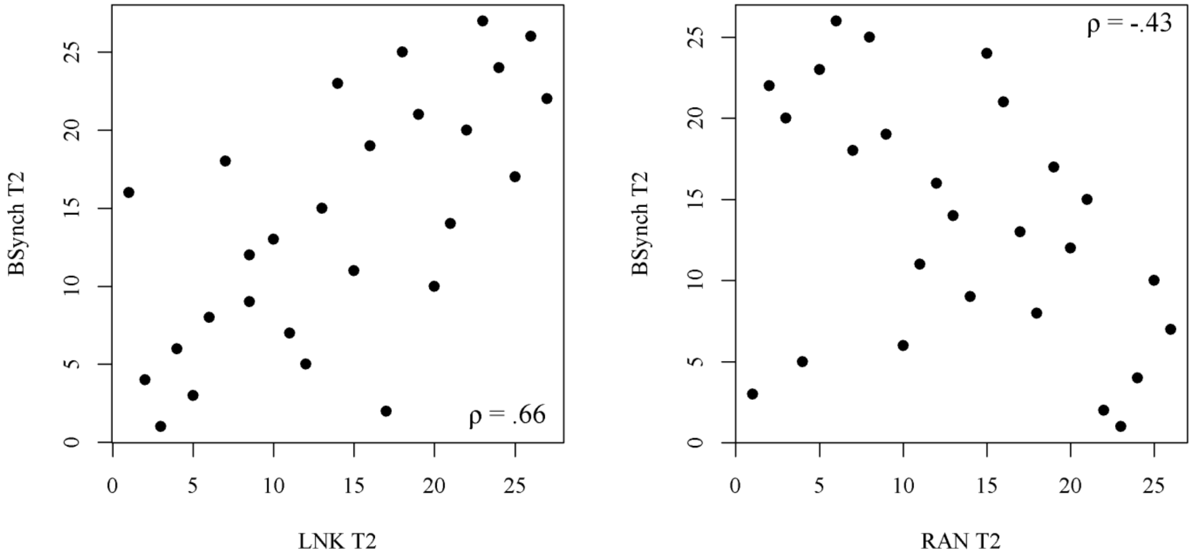

Figure 5.1.2. Partial Spearman correlations between the BSynch task at T2 and reading predictors at T2

5.1.3.2.1.3. The BSynch task at T3

Finally, none of the reading predictors correlated with the BSynch task at T3. The results of these correlations are presented in Table 5.1.5.

Table 5.1.5. Spearman correlations between the BSynch task at T3 and the remaining reading predictors at T3

		BSynch T3			
		n	***ρ***	***p***	***FDR***
T3	**RAN**	29	-.02	.93	-
	PWRep	31	.21	.27	-
	PhDel	29	-.10	.60	-
	DSB	30	.25	.18	-

DSB = Digit span backward; PWRep = Pseudoword repetition; PhDel = Phoneme deletion/elision

5.1.3.2.2. Median-comparison analyses

In this section, our aim was to further explore from the median-comparison perspective the inter-dependency relations found with the correlation analyses presented in section 5.1.3.2.1. The criteria for the selection of the variables ($\rho \geq .30$ and/or $p \leq .10$) were explained in section 5.1.2.3.2 of this chapter. Accordingly, the following relations were further examined:

- BSynch T1 with LNK T1, Pseudoword repetition T1, LNK T1, Pseudoword repetition T2 and Pseudoword repetition T3

- BSynch T2 with RAN T2 and LNK T2

We did not further explore the BSynch task at T3, since none of the correlations met our criteria for further examination.

As mentioned in section 5.1.2.3.1, children were considered Synchronisers (Synch) when their *p*-value in the Rayleigh's test for the BSynch task was below the established .05 threshold and Non-synchronisers (Non-synch) when the *p*-value was larger (see Figure 5.1.3 for beat performance of representative subjects of each group). Table 5.1.1 shows individual participant's group belonging as a function of the *p*-value resulting from the Rayleigh's test along the testing times. As shown in this table, more than 90% of the children followed the expected longitudinal trajectory in the task (i.e. either stayed in the same group or went from Non-synch group to the Synch group)[1].

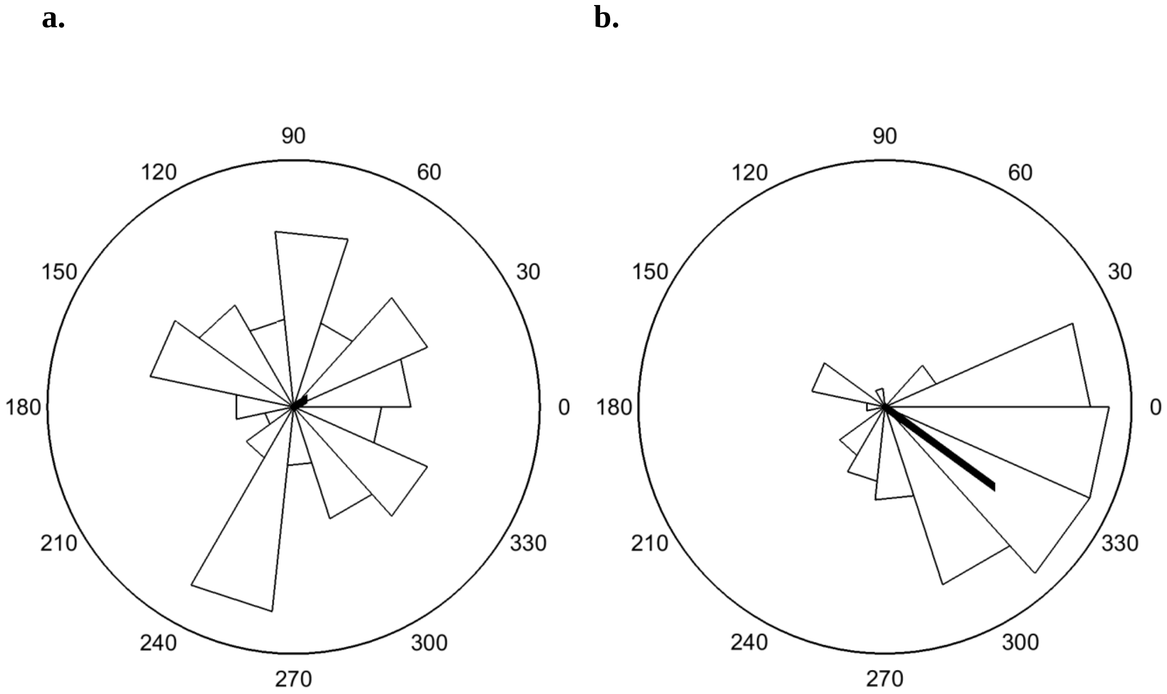

Figure 5.1.3. Phase consistency histogram of two participants' drumbeats in a trial relative to stimulus (0º). The thick black line depicts the mean phase vector (i.e. the consistency between the time of the beat and the time of stimulus onset). a) The Non-synchroniser drumbeats are distributed randomly along the cycle, what is reflected in the short mean phase vector. b) The drumbeats of the Synchroniser concentrate around the stimulus region. This is reflected in increased length of the mean phase vector.

5.1.3.2.2.1. Synchronisers vs. Non-synchronisers at T1

In T1, 15 and 27 children were categorised as Synchronisers and Non-synchronisers, respectively (Table 5.1.1.). Based on the results reported in the correlation analyses (section 5.1.3.2.2), we tested the effect of the Group factor (Synch vs. Non-synch) on the performance in

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[1] One child (subject 21) showed the opposite pattern from T1 to T2 (from Synchroniser to Non-synchroniser). Such was also the case of three children (subjects 3, 10 and 37) from T2 to T3, but since no significant correlations were found with the BSynch task at T3, the Group at T3 was not used in any further analysis. As stated in section 5.1.2.3 (*Data analysis)*, longitudinal outliers were excluded based on the absolute value of Rayleigh's *z*-value before performing any statistical analysis on the data. Nevertheless, whenever the Group at T2 was involved as a factor in an analysis, we performed it newly without subject 21 obtaining the same results (see table A5.1. in section A5 of the Appendix).

the LNK and Pseudoword repetition tasks both at T1 and at T2, and on the Pseudoword repetition task at T3. Results of the Mann-Whitney tests can be seen in Table 5.1.6. This table also presents the results of the multiple non-parametric ANCOVAs performed on the same data, but controlling for age and IQ. As can be seen in the table, including age and IQ in the analysis did not change the results. A visual depiction of the differences between the groups in the selected tasks can be seen in Figure 5.1.4.

Table 5.1.6. Results of the non-parametric tests comparing performance in the tasks measuring the reading predictors across testing times as a function of group belonging (Synch vs. Non-synch) at T1

		Median		**Mann-Whitney**			**(n-p) ANCOVA**		
		S	**NS**	**U**	***p***	**FDR-*p***	***h***	***p***	**FDR-*p***
T1	**LNK**	18.93	13.94	91	<.01*	.03*	2.68	<.01*	.01*
	PWRep	18.88	16.27	123	<.01*	.01*	2.68	.05*	.06
T2	**LNK**	22.00	19.79	79	.03*	.06	2.62	.04*	.06
	PWRep	15.36	13.46	96	.08	.08	2.63	.33	.33
T3	**PWRep**	17.90	14.92	66	.04*	.06	2.63	.01*	.02*

n-p = non-parametric; NS = Non-synchroniser; PWRep = Pseudoword repetition; S = Synchroniser

In order to ensure that our analyses were not contaminated by extreme observations, we explored the separate plots to detect possible outliers. Data visualization of the median comparison for the LNK task at T1 (left plot of Figure 5.1.4) suggested that one of the children in the Synch group could be an outlier (subj 40 in Table 5.1.1). We repeated this analysis without this child and confirmed that the difference between the groups was still significant (U = 7.5, p = .002). Such was also the case of two observations in the comparison between the group means in the Pseudoword repetition task at T3 (subjects 21 and 25 in the Synch group; see right plot of Figure 5.1.4). In the same line, we repeated the analysis without these participants and confirmed that the between-group difference was still significant (U = 50, p = .03).

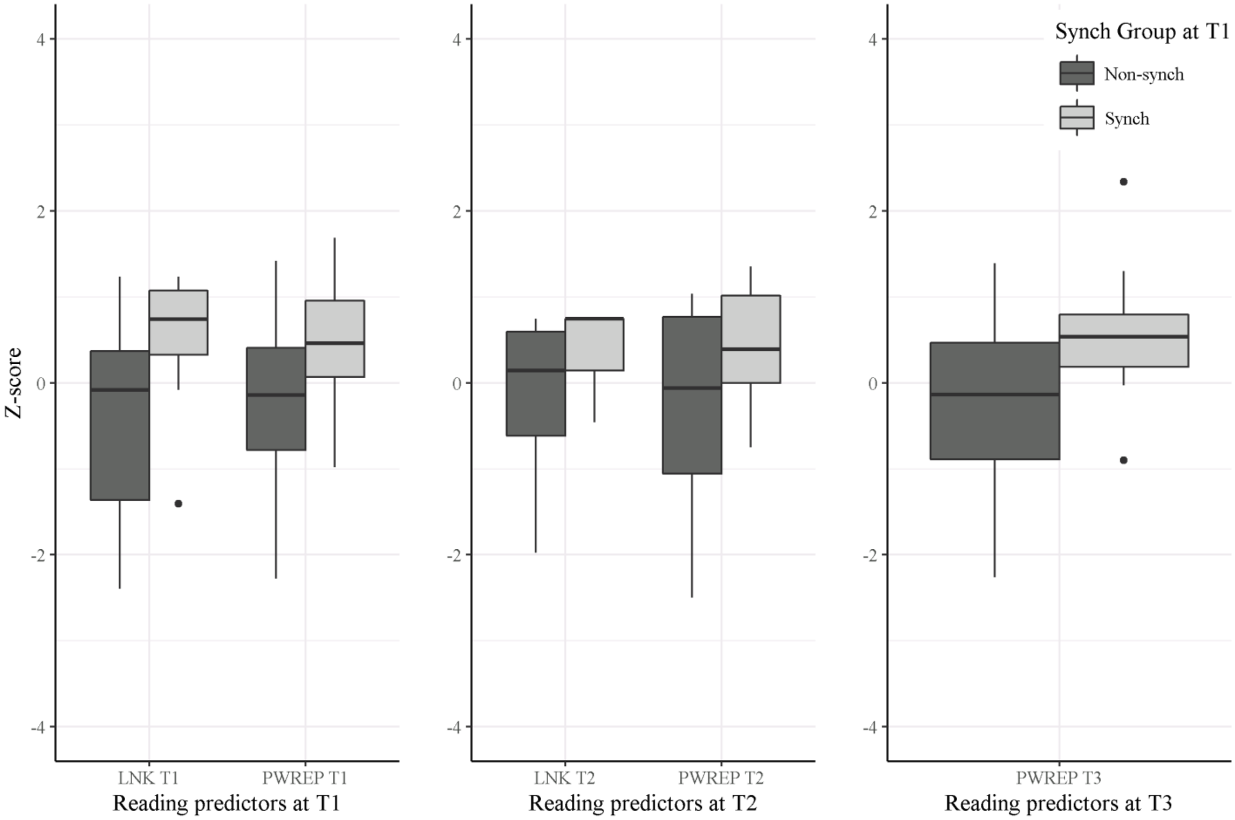

Figure 5.1.4. Boxplots representing the differences in performance in the tasks measuring reading predictors as a function of Group at T1 (Synch vs. Non-synch). The left column represents such differences transversally (within T1) and the central and right columns longitudinally (T2 and T3, respectively). Possible outliers are marked with a dark circle and represent data points 1.5 times outside the interquartile range.

5.1.3.2.2.2. Synchronisers vs. Non-synchronisers at T2

At T2, 12 children were classified as Synchronisers and 17 as Non-synchronisers (see Table 5.1.1). The Mann-Whitney tests confirmed that there was a significant difference between the groups in the LNK and RAN tasks at T2, such that the Synch group knew more letters of the alphabet and took less time to complete the RAN task as compared to the Non-synch group (see Table 5.1.7 for complete output of these analyses). The non-parametric ANCOVAs confirmed that children’s age and IQ differences did not explain the group differences in the tasks measuring reading predictors at T2.

Table 5.1.7. Results of the non-parametric tests comparing performance in the tasks measuring the reading predictors at T2 as a function of group belonging (Synch vs. Non-synch) at T2

		Median		**Mann-Whitney**			**(n-p) ANCOVA**		
		S	**NS**	**U**	***p***	**FDR-*p***	***h***	***p***	**FDR-*p***
T2	**LNK**	22.50	20	121	.01*	.03*	2.98	.02*	.03*
	RAN	46.74	66.44	121	.03*	.03*	2.97	.03*	.03*

n-p = non-parametric; S = Synchroniser; NS = Non-synchroniser

Data visualization suggested that one of the children in the Non-synch group (subj 4) and one of the children in the Synch group (subj 17) could be outliers in the RAN task at T2 (Figure 5.1.5, most left boxplot). We repeated the analysis without these subjects and confirmed that the difference was still significant (*U* = 109, *p* = .01).

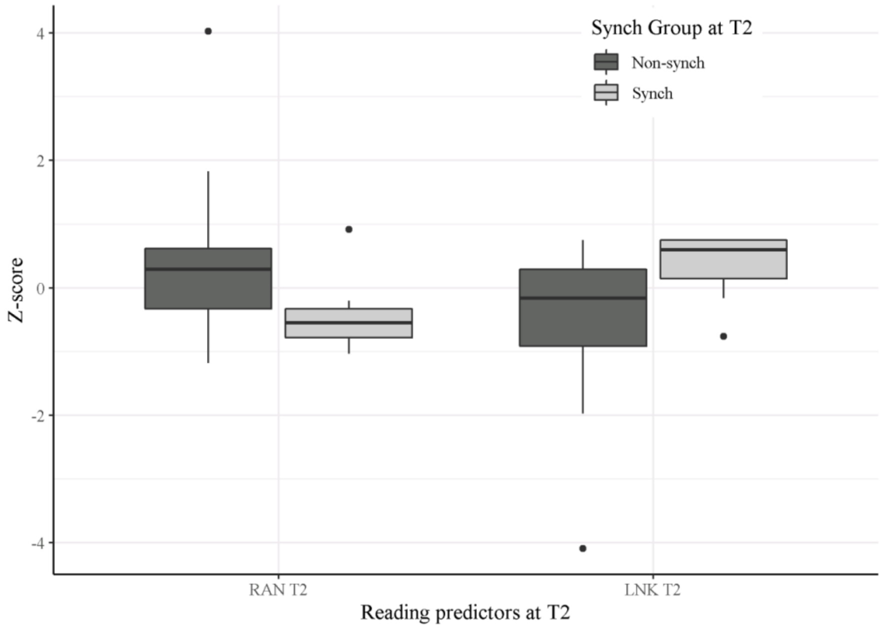

Figure 5.1.5. Boxplots representing the differences in performance in the tasks measuring reading predictors at T2 as a function of Group at T2 (Synch vs. Non-synch). Possible outliers are marked with a dark circle and represent data points 1.5 times outside the interquartile range.

Regarding the LNK task at T2 (Figure 5.1.5), the boxplot chart suggested again that two of the children could be outliers in this task (subj 7 from the Non-synch group and subj 17 from the Synch group). The Mann-Whitney test without these children also resulted significant (U = 3.5, p = .001).

5.1.3.3. Relation between the BSynch measure and reading outcome at T3

Partial correlation analyses of the BSynch task at T1, T2 and T3 and Reading performance at T3

None of the coefficients (or corresponding p-values) for the pair-wise correlations between the BSynch measure at T1, T2 or T3 and Reading output at T3 met our requirements for further analyses with median comparison methods (all ρs ≤ .30; all ps ≥ .10; see Table 5.1.8).

Table 5.1.8. Results of the partial Spearman correlations between the BSynch task at T1, T2 and T3 and Reading outcome at T3.

		Reading T3		
		n	**ρ**	**p**
	T1	33	.01	.96
BSynch	**T2**	25	.17	.39
	T3	31	-.29	.14

5.1.4. Discussion

The current longitudinal experiment explored the value of behavioural rhythmic abilities to predict children’s reading readiness and future reading skills. Rhythmic abilities were assessed using a behavioural task that measured the ability of the children to synchronise to an external beat (BSynch) within the delta frequency range (at 1.67 Hz). Our results confirmed our hypotheses only partially: while rhythmic abilities at early (pre-reading) stages were related to classical reading predictors transversally and longitudinally, their relation with classical reading predictors weakened along the years, such that no relation was found between them right after they had received their first year of formal reading instruction (at the end of Grade 1). Moreover, none of the BSynch measures taken along the years was able to predict reading skills at T3.

At the first testing time of the current study (T1), children who significantly synchronised their beats to the external stimulus showed better performance in the letter name knowledge

(LNK) and the Pseudoword repetition tasks. The relation of the BSynch task with these classical reading predictors held longitudinally, such that children that were Synchronisers at T1 also knew more letters of the alphabet at T2 (note that the LNK measure was not included in T3 due to ceiling effects) and showed increased phonological short-term memory at T2 and T3. Similarly, children who were Synchronisers at T2 performed better in the LNK and RAN transversally (at T2), although the group at T2 was not able to predict performance longitudinally (at T3). The relation between rhythmic synchronization and phonological short-term memory and the RAN in pre-reading stages replicates previous results in the literature (Carr et al., 2014). Unfortunately, we were not able to test phonological awareness at these early stages[2], and hence cannot provide evidence in this sense. By contrast, our results confirmed the hypothesis that early rhythmic skills would not only be related to previously reported phonological predictors, but also to a more orthographical predictor such as LNK. Overall, our results are in line with previous studies testing pre-schoolers and showing that rhythmic skills at these ages could be a good index of reading readiness (Moritz et al., 2013; Carr et al., 2014). The current study shows that up to this point in development (i.e. in pre-reading stages) measuring rhythmic abilities with a child-friendly task could be used as a proxy measure for other linguistics (less child-friendly) tasks that will later predict reading performance. Furthermore, our results support a tight relation between rhythmic abilities and emerging phonological processing (as measured via phonological short-term memory), supporting recent accounts on the importance of rhythmic sensitivity for the development of phonological skills, and in turn for reading acquisition (Goswami, 2011; Lallier et al., 2017).

By contrast, rhythmic abilities at T3 were not transversally related with any reading predictor. This result, together with the fact that the synchronization task measured along the testing times did not predict reading performance at T3, is at odds with previous studies using similar paradigms that showed a significant relation between the development of rhythmic skills and reading performance (e.g. Dellatolas et al., 2009; Holliman et al., 2010; Lundetræ & Thomson, 2017). We considered several explanations for the absence of this expected relation.

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[2] Note that our children could not complete the phonological awareness task in T1 or T2, and hence the rhythm-phonology relation could only be tested with the phonological short-term memory task. The fact that children were not able to complete the task until they were able to read is in line with the idea that the relation between phonological awareness and reading acquisition is reciprocal rather than unidirectional (Stuart & Coltheart, 1988).

First of all, our modest sample size did not allow us fitting more sophisticated models (e.g. structural modelling such as Path analysis), since this would have derived in a poor observations-to-parameters ratio. Thanks to its ability to model indirect relations, structural modelling would allow us testing the hypothesis that the relation between rhythmic abilities and reading is mediated by other reading predictors (most likely phonological short-term memory and knowledge of the letters of the alphabet in our specific experiment). Our data suggests that the relation between rhythmic skills and reading might not be as direct as required to be measurable with small (but common in the children literature) sample sizes. Longitudinal (likely behavioural-only) designs with large cohorts will be necessary to model such relationships reliably, since modelling this relation was not the only aim of this study (see Experiments 1 to 3). Related to this, the absence of the relation between rhythmic skills and reading performance could also be explained if we take into account the multi-factorial nature of reading (e.g. Menghini et al., 2010; Peyrin et al., 2012). Indeed, it has been consistently stated that single factors will never explain all reading variability (Bishop, 2006; Muter, Hulme, Snowling, & Stevenson, 2004; Pennington, 2006). In this line, rhythmic sensitivity might be an indicator of poor reading only if accompanied by other poor abilities, i.e. when no compensatory mechanisms are deployed. This is supported by the previous study by Lundetræ and Thomson (2017), which found that rhythmic skills at the beginning of Grade 1 did not predict reading achievement one year later, but that adding this factor to a logistic regression model that included the rest of classical predictors significantly improved the power of the model to classify poor readers. Overall, we believe that developmental reading disorders, similarly to other developmental pathologies, could be considered as the product of the interaction between deficient and compensatory mechanisms (Snowling, 2008; Thomas & Karmiloff-Smith, 2003). Consequently, the influence of rhythmic skills on literacy acquisition might be best explored together with the influence of other reading predictors. Again, the modest sample size of the current experiment did not allow us performing such analyses keeping an acceptable level of statistical power, and future studies might look into this exciting possibility.

In any case, the weakening of the relation between the rhythm task and the remaining reading predictors along the years cannot be explained in terms of sample size, since this (and hence our statistical power) was very similar across the testing times. We considered several explanations for this result, mainly the characteristics of our sample, the stimulation rate of the rhythm task, and the periodic and non-linguistic nature of our stimulus in interaction with the reading acquisition stage of the children at the last testing time (T3).

First, we believe it is important to note that the only study reporting a significant relation between pre-reading rhythmic skills and future reading achievement included poor readers (Lundetræ & Thomson, 2017). The fact that our children were typically developing children is an aspect to consider when interpreting the absence of significant results for our sample. Although there is no reason to believe that rhythmic sensitivity is not important for typical reading acquisition (Wood, Wade-Woolley, & Holliman, 2009), reading variability is reduced in typical as compared to pathological populations, and our BSynch measure might not have been sensitive enough to capture subtle differences in reading performance at T3. Related to this point, it is also interesting to highlight that the BSynch task correlated with itself in consecutive years (T1-T2, T2-T3), but not between T1 and T3. Rhythmic skills tend to improve with age (Colling et al., 2017; Drake et al., 2000; McAuley et al., 2006), but in the gap from two years, some of the children improved, while performance did not change or even decreased slightly in other children (see Table 5.1.1). It is possible that more sophisticated measures that take into account the developmental trajectory of children's rhythmic skills (e.g. growth curve analysis) are more predictive of the development of reading skills. Future analyses will reveal if such dynamic measures are indeed more informative than static measures such as the ones we employed in the current work.

Second, we believe that the specific tempo at which synchronous tapping was tested might have influenced our results. We measured synchronization to beats at a rate of 1.67 Hz, as used in the study by Carr et al. (2014). This study also tested synchronization at 2.5 Hz, but the authors only presented the results for the children's averaged performance in both conditions (i.e. no separate results for the different frequencies is available). By contrast, Lundetræ & Thomson (2017) used two different tempos (1.5 Hz and 2 Hz) and reported that whereas the stimulus at 1.5 Hz improved their logistic model's ability to classify children as poor readers, the stimulus at 2 Hz did not. In the same line, another study reported no differences between dyslexic and typically developing children in phase consistency while tapping to a beat at 2 Hz (Colling et al., 2017). The mixed results depending on the frequency tested suggest that, although within the same frequency band (the delta band), rhythmic entrainment to some specific frequencies might contribute to literacy acquisition, while entrainment to others might not. Importantly, the influence of rhythmic sensitivity to the different frequencies might change with age. We hope that future studies will help disentangling the functional meaning of such differences.

Finally, our task's synchronization rate was perfectly periodic (note that this is a requirement in behavioural online synchronization tasks) and non-linguistic, reason for which it is interesting to compare the results of the current experiment with the results of the neural tasks (Experiment 3). While we found a relation between reading and delta-band neural sensitivity to speech, which is provided with verbal information and with a less predictable amplitude envelope (see Discussion of Experiment 3), we failed to find such relation for delta-band sensitivity to periodic non-linguistic stimuli, both at the neural (Experiment 3) and at the behavioural (current experiment) levels. This, again, could point towards the fact that the delta rhythms-reading relation is mediated by the verbal nature and/or temporal characteristics of the speech signal. In addition to this, we believe that our results for the behavioural task provides new insightful evidence on the developmental trajectory of the rhythm-reading relation, since we tested the contribution of behavioural rhythmic sensitivity not only to reading achievement at T3, but also to reading readiness (i.e. the relation with other reading predictors) across the testing times[3].Indeed, the fact that we found that behavioural synchronization to the periodic delta-rhythm was related to other reading predictors in very early stages of the reading acquisition process, but not at the of end Grade 1 (when the children had already received one year of reading instruction), suggests that the contribution of rhythmic sensitivity to reading might change as children acquire reading experience, and specially as a function of the phonological demands required in the specific moment of the reading acquisition course (see Lundetræ & Thomson, 2017 for a similar argument). Actually, there is abundant evidence that learning to read is a dynamic process in which the weight of the different reading predictors will change as children advance through the different reading stages (see Nagy, Carlisle, & Goodwin, 2014 for a review). Actually, there is evidence showing that, at least for typical reading, the contribution

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[3] Note that we tested the relation of neural rhythmic sensitivity across the testing times with reading and phonological awareness at T3 only. We were not able to test its relation with the other reading predictors across the years due to the involvement of excessive comparisons (i.e. multiple electrodes) for our reduced sample size,

of phonological awareness could be restricted to very early stages of reading development, namely to the alphabetic phase, based mainly on the implementation of letter-sound correspondences (Nagy, Berninger, & Abbott, 2006). By contrast, other predictors such as morphological knowledge have been proven to exert an important influence on reading skills across the school years (Berninger, Abbott, Nagy, & Carlisle, 2010). Since our children were readers of a highly transparent orthography, it is possible that at T3 they were already past the alphabetic phase, and into a more advanced reading phase on which they already relied on, for example, morphological/lexical knowledge (Frith, 1986; Marsh, Friedman, Welch, & Desberg, 1981; Nagy et al., 2014). Note that, if (purely acoustic) rhythmic sensitivity is fundamental for the formation of phonological representations (Goswami, 2011), and the quality of these representations is essential *mostly* during very early (decoding) reading stages in typical reading development, it is not surprising that its contribution decreases notably as children move forward to more advanced reading stages. In other words, once children are past the decoding phase, the relation between reading and purely perceptual indexes such as rhythmic sensitivity to non-linguistic stimuli might be modest, or already non-existent, since at this stage the relation might be already mediated by higher linguistic processes. For all this, we are inclined to believe that, at least in samples of non-pathological readers of transparent orthographies, stimuli with verbal (phonological) information might be best to capture reading variance when children are already past the very initial stages of reading acquisition, while the contribution of perceptual-only rhythmic sensitivity might be more visible at very initial stages of formal reading instruction (for example in the middle of Grade 1 in the Basque Country). Nevertheless, it is also possible that the difference in predictive power of our speech *versus* the AMs and the BSynch task is not rooted at the presence/absence of verbal information, but at the different temporal structure of the stimuli. The AE of the natural speech does not contain perfectly periodic modulations, while the AE of the AMs and of the BSynch task is perfectly rhythmic (see Discussion of Experiment 3). Again, future studies might shed light into the particularities of the rhythm-reading relation and examine the possibility that perceptual and verbal factors influence differently reading performance along the literacy acquisition process.

Lastly, we must highlight that, although we were not able to proof the longitudinal relation between rhythmic skills and future reading, remediation programmes based on practising synchronised tapping have until now offered acceptably successful results in improving children’s phonological awareness (Bhide, Power, & Goswami, 2013; Degé & Schwarzer, 2011; Slater et al., 2014). This suggests that the influence of rhythm on reading development is there and, although not as direct as expected, future studies could optimise their paradigms and testing moments, and specially test larger cohorts, to establish the exact particularities of such relation.

5.2. Conclusions of Chapter 5

Our longitudinal study was the first to test the value of a behavioural rhythmic synchronization (BSynch) task at delta rates for the prediction of reading readiness and reading skills in typically developing children. The BSynch task at 1.67 Hz was tightly related to letter name knowledge and phonological short-term memory at the end of the second-to last year of kindergarten (T1) and was able to predict the children's performance in these tasks one year later (T2). This evidence is in line with previous studies showing that rhythmic synchronization is a good index of reading readiness in pre-readers (e.g. Moritz et al., 2013; Carr et al., 2014). By contrast, we found a slight weakening of the relations between the rhythmic task and the rest of predictors at T2, which ended in its lack of predictive power at T3, time at which children had already receive reading instruction. Importantly, performance in the BSynch task across the years was not able to predict reading outcome at T3. Although we are of the opinion that this result might be deeply influenced by the characteristics of our sample (typically developing children) and the tempo at which rhythmic synchronization was tested (Colling et al., 2017; Lundetræ & Thomson, 2017; Carr et al., 2014), we believe that it is possible that the rhythm-reading relation changes along development and depends tightly on the reading stage at which children are tested. In this line, we hypothesised that the relation between pure acoustic rhythmic sensitivity and reading should be more prominent in early stages of literacy acquisition, when reading relies deeply on letter-to-sound mapping processes (Frith, 1986; Marsh et al. 1981), and less important when reading strategies undergo a swift to higher-order linguistic aspects (Nagy et al., 2014). This idea is supported by our Experiment 3, since we found a relation between reading and neural rhythmic sensitivity to a phonologically rich stimulus (Natural speech), but not to non-linguistic amplitude modulations. Overall, our results suggest that the relation between rhythm and reading, at least in typically developing children of transparent orthographies, could be mediated by verbal information once they pass the initial decoding stage. Notwithstanding, to provide definite support for this hypothesis it is necessary to conduct studies in which the verbal and the temporal complexity factors can be adequately disentangled, an initiative that future studies will hopefully undertake.

Chapter 6: Brain and behavioural rhythms: Different sides of the same coin?

Based on the mixed results of our previous Experiments 3 and 4, our main goal with this chapter was to examine if overt behavioural rhythmic synchronization tasks could be used as a proxy of covert neural entrainment processes, and *vice versa*, as previously suggested in the literature. To this aim, we directly compared our rhythm sensitivity tasks at the neural level with our rhythmic sensitivity task at the behavioural level. Accordingly, in the following pages we strive to answer our last research question:

- Research question 1: How does oscillatory activity in response to speech and to auditory stimuli modulated at rates relevant for speech perception develop during childhood? (Experiments 1 and 2, respectively)
- Research question 2: What is the contribution of brain oscillatory activity to reading acquisition? (Experiment 3)
- Research question 3: What is the contribution of rhythmic behavioural skills to reading acquisition? (Experiment 4)
- **Research question 4: Can we use brain rhythms and behavioural rhythms as *equivalent* measures for the prediction of reading achievement? (Experiment 5)**

6.1. Experiment 5: The relation between coherence to auditory signals and behavioural rhythmic skills

6.1.1. Introduction

As presented along this doctoral work, reading abilities have been related both to neural (Abrams et al., 2009; J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Molinaro et al., 2016) and to behavioural (Corriveau & Goswami, 2009; Huss et al., 2011; Thomson et al., 2006; Thomson & Goswami, 2008; Tierney & Kraus, 2013) rhythmic synchronization. Accordingly, recent theories such as the *temporal sampling* (TS) framework (Goswami, 2011, 2018) have proposed that the neurobiological basis of rhythmic sensitivity in behaviour would rely on the ability of the brain to synchronise to the slow rhythms of speech (and other auditory signals). Within the range of low-frequency bands, impairments in the delta band (<4 Hz) have been suggested to play a causal role in the development of reading related disorders (Goswami, 2011; Lallier et al., 2018, 2017). This is not surprising given that crucial information for the appropriate perception of speech such as stress (Curtin, Mintz, & Christiansen, 2005; Leong et al., 2011) falls within the delta range (~2 Hz; Ghitza & Greenberg, 2009). Nevertheless, to our knowledge very few studies have assessed jointly neural and behavioural rhythmic sensitivity within the delta frequency range to assess their comparability (Colling et al., 2017; Tierney & Kraus, 2013a; Carr et al., 2014).

For example, a study in adolescents showed that the *inter-trial phase consistency* of complex auditory brainstem responses (cABRs) to periodically-presented synthesised syllables was correlated with the ability of the participants to tap in synchrony to beats at 1.5 and 2 Hz rates, such that participants with more consistent cABRs performed better in the tapping to a beat task (Tierney & Kraus, 2013a). With a very similar procedure, another study extended this evidence to a group of pre-reading 5-years-old children (Carr et al., 2014). This study showed that children who performed better in a tapping to a beat task at 1.67 and 2.5 Hz (delta band) showed more consistent cABRs to the envelope of synthesised syllables presented at intervals of 81 ms (~12 Hz) both in quiet and in noise backgrounds. Moreover, they reported that children that performed better in the behavioural and the neural tasks also showed better performance in a battery of reading prediction tasks (phonological short-term memory, phonological awareness and RAN). This evidence supports the idea that the ability to track the speech envelope *within* syllabic units could be reflected behaviourally in the ability to synchronise to an external rhythm, and that both would be equally related to reading readiness. Importantly, due to the difficulty that involves testing very small children with electrophysiological techniques, if this relation were true, behavioural rhythm skills could be used as a proxy measure of the phase consistency of the brainstem's responses, which has been previously related to reading (White-Schwoch & Kraus, 2013; Wible, Nicol, & Kraus, 2004). Nevertheless, the brainstem inter-trial phase consistency measure used in these studies cannot be compared to the coherence measures used by the studies examining cortical auditory temporal processing that have been reviewed throughout this doctoral thesis (e.g. Bourguignon et al., 2013; Howard & Poeppel, 2010; Molinaro et al., 2016; Peelle et al., 2013). Indeed, whereas these studies tested the phase relation between the brain signal and the auditory signal of interest at different frequency bands corresponding to the rates of appearance of relevant linguistic units (i.e. stress, syllables and phonemes), studies that used inter-trial phase coherence of the cABR measured the consistency of the brainstem to respond to the spectro-temporal features *within* the linguistic stimuli (syllables), which were presented at rates of 12 Hz (Tierney & Kraus, 2013a; Carr et al., 2014). The difference between these methods lies fundamentally on the physiological aspects of the responses measured and on the stimuli presentation rate. On the one hand, the underlying physiological mechanisms of the responses measured are obviously different. The cABR is (putatively) driven by activity within the inferior colliculus (Chandrasekaran & Kraus, 2010; Warrier, Abrams, Nicol, & Kraus, 2011; but see Coffey, Herholz, Chepesiuk, Baillet, & Zatorre, 2016 for an interesting discussion of this issue) which, thanks to its high timing precision, has been suggested to capture optimally the spectro-temporal features of the stimulus (Skoe & Kraus, 2010; Warrier et al., 2011). By contrast, (cortical) coherence measures activity originated in the cortex. On the other hand, and derived from the previous aspect, the optimal presentation rate of the stimulus that best captures the responses at the level of the cortex and of the brainstem is different. As opposed to cortical auditory responses, which are optimally obtained with slower stimulation rates, the cABR is best captured with faster stimulation (Burkard, Eggermont, & Don, 2007). Accordingly, experiments measuring brainstem responses must accelerate the presentation rate of the stimuli, and temporal coherence to natural stimuli such as natural language is hence difficult to test (Skoe & Kraus, 2010). Overall, the results that the cABRs to syllables predicts performance in a rhythm synchronization task is highly interesting, but can only be complementary for studies measuring coherence to the slow temporal components of speech.

Another study examined EEG power and phase measures in response to auditory beats while dyslexic and non-dyslexic participants performed a tapping in synchrony task (Colling et al., 2017). Here it is important to note that, in behaviour, it has been shown that the motor dexterity component of rhythm production tasks does not explain the relation between rhythm and reading, and that this relation must be therefore mediated by the sensory component of the tasks (Thomson & Goswami, 2008). Based on this evidence, Colling et al. (2017) used steady-state evoked potentials or SS-EPs (Nozaradan et al., 2015) to discriminate the neural motor and sensory contributions to behavioural rhythmic production, and to test their (independent) relation with several reading predictors and with reading achievement. To this aim, they presented participants with auditory periodic beats at a rate of 2.4 Hz (i.e. within the delta band). Participants listened to the stimuli in three different conditions: two conditions in which participants had to tap to every second beat (i.e. at 1.2 Hz) either with their right (dominant) or with their left (non-dominant) hand, and a listening-only condition. This paradigm allows obtaining three brain-related measures: movement-related activity (at 1.2 Hz for the tapping condition), representation of the physical beat (at 2.4 Hz) and internal representation of a beat that is not present in the physical stimulus (sensory-motor integration; 3.6 Hz). For all conditions, they found that the group of dyslexic showed a different preferred phase of entrainment as compared to the control children. Regarding the power measures, they report that the SS-EPs of the groups were not different when movement related activity was concerned, but that they differed in the listening only condition at 2.4 Hz (representation of the beat). Finally, they found a marginal group difference when children had to tap with their right hand (the dominant hand) at 3.6 Hz, such that the amplitude of the response was larger in the group of control children as compared to the dyslexic children. Importantly, they found significant correlations between brain activity during right-hand tapping and several phonological and reading measures. These results suggest a neural sensori-motor integration origin of the temporal processing deficit in dyslexia (Colling et al., 2017). Nevertheless, regarding behaviour, they did not find any significant differences in tapping performance between the dyslexic and control groups (the participants were actually matched in behaviour). Although the authors do not report direct correlations between the tapping performance and the neural response, the fact that they found differences in EEG phase angle and power (SS-EPs) but not in behaviour suggests that the measures were not significantly correlated.

In conclusion, the results of previous studies highlight relevant results for the reading development field, but none of them compared directly phase consistency measures related to rhythm sensitivity at the delta band in behaviour and in the brain. Importantly, finding a behavioural correlate of neural oscillatory activity in low-frequency bands could be highly valuable for early assessment, prevention and remediation of speech-related developmental disorders given the intrinsic difficulties of testing very young children with electrophysiological techniques.

This study

The aim of this study was to directly compare phase consistency measures in neural and behavioural tasks examining rhythm sensitivity at the delta frequency band during early childhood. To this goal, we assessed the performance of a cohort of typically children developing children in three testing times along two full years (T1: 4-5 years old; T2: 5-6 years old; T3: 6-7 years old) in a behavioural tapping to a beat task at 1.67 Hz. We also collected EEG data to measure their brain oscillatory responses to the low-frequency components of natural speech and to non-linguistic auditory stimuli amplitude-modulated (AM) at 2 Hz.

Hypotheses

No study has directly compared phase coherence measures in the delta band at the brain and at the behavioural level to directly assess their comparability, and our hypotheses were hence based on previous separate evidence for this type of tasks and on experiments assessing both, but using different measures. Based on previous evidence showing that dyslexics show impaired rhythmic sensitivity at the delta frequency range both at the behavioural (e.g. Corriveau & Goswami, 2009; Thomson & Goswami, 2008) and at the neural (J. A. Hämäläinen et al., 2012; Molinaro et al., 2016; Power et al., 2016, 2013) levels, we expected that phase consistency measures at both levels would correlate significantly. By contrast, based on previous evidence that found atypical neural activity in response to periodic beats at rates within the delta band in dyslexics as compared to control children, but no differences in performance on a tapping to a beat task (Colling et al., 2017), we also considered the possibility that these tasks were not as related as previously implied (Corriveau & Goswami, 2009; Goswami, 2011). This last hypothesis was also based on our own results of previous experiments showing that coherence to natural speech in the delta band (0.5 Hz) predicted reading achievement (Experiment 3), while coherence to periodic AMs (Experiment 3) or tapping to a beat in synchrony did not (Experiment 4).

6.1.2. Materials and methods

6.1.2.1. Participants

Coherence to Natural speech and BSynch

At T1, 26 children (age *M* = 5.15; *SD* = .30; 14 males) completed both the coherence to Natural speech task and the BSynch task. Eight children were categorised as Spanish dominant and 18 as Basque dominant. Five of the children were left-handers.

Twenty-eight children completed the tasks at T2 (age *M* = 5.89; *SD* = .35; 13 males). Eighteen and 10 children were characterised as Basque or Spanish dominant, respectively. Five of the children were left-handers.

Finally, 26 children completed both tasks at T3 (age *M* = 6.98; *SD* = .32; 13 males). Eighteen and eight children were characterised as Basque or Spanish dominant, respectively. Three children were left-handers.

Coherence to 2-Hz amplitude-modulated (AM) signals and BSynch

As reported in Experiment 2 (Chapter 4), the data for the 2-Hz AM condition was not available at T1 due to a technical problem.

Twenty-five children (age *M* = 5.86; *SD* = .33; 12 males) completed the coherence to the 2-Hz AM signal and the BSynch task at T2. Seventeen children were Basque dominant and eight Spanish dominant. Three of the children were left-handers.

At T3, 32 children completed both tasks (age *M* = 6.98; *SD* = .33; 16 males). Twenty-one and 11 children were characterised as Basque or Spanish dominant, respectively. Four children were left-handers.

6.1.2.2. Stimuli and procedure

The stimuli and procedure for the Beat synchronization (BSynch) task have been presented in section 5.1.2.2.6 of Chapter 5. The procedure for the EEG acquisition can be found in section 3.2.2.2 of Chapter 3. Similarly, the EEG tasks' stimuli and procedure were described in sections 4.1.2.2 (Natural speech) and 4.2.2.2 (AM signals) of Chapter 4.

6.1.2.3. Data analysis

The analysis of the individual tasks can be found in the corresponding experiments (see paragraph above).

Importantly, as explained in section 5.1.3 (*Descriptive statistics and longitudinal outlier removal*) of Chapter 5, the performance of some of the children in the BSynch task suffered an odd detriment from the longitudinal point of view (see Table 5.1.1, Chapter 5), and their data was not further analysed. Accordingly, at T2 the data of six children (subjects 3, 10, 24, 31, 38 and 40) was removed from the joint analysis of the Natural speech and the BSynch tasks (final *n* for T2 analysis = 22). Similarly, the data of one child at T3 (subject 6) was not further analysed (final *n* for T3 analysis = 25). Regarding the analysis of the AM signal at 2 Hz, following the same criterion the data of six (subjects 3, 10, 24, 31, 38 and 40) and two (subjects 6 and 16) children were removed from the analyses of T2 and T3, respectively (final *n* for T2 analysis: 19; final *n* for T3 analysis: 30).

In order to compare the performance in the neural and the behavioural tasks, we computed partial Spearman correlations (controlling for age and IQ) within each testing time between the BSynch task and the coherence to speech at 0.5 Hz in temporal electrodes on the one hand, and the BSynch task and coherence to 2-Hz AM signals in temporal electrodes on the other hand.

6.1.3. Results

Detailed results for the individual tasks can be consulted in sections 4.1.3 (coherence to Natural speech) and 4.2.3 (coherence to 2-Hz amplitude-modulated [AM] signals) of Chapter 4, and in section 5.1.3 of Chapter 5 (BSynch task).

Z-scores of the children across the testing times in the BSynch and the coherence to Natural speech tasks after outlier removal can be seen in Table 6.1.1, while Table 6.1.2 presents the *z*-scores for the coherence to the AM at 2 Hz and the BSynch tasks.

Regarding the joint analysis of the behavioural and neural tasks, the results for the correlations between the BSynch task and the coherence to Natural speech task are presented in section 6.1.3.1. Section 6.1.3.2 presents the results for the joint analysis of the BSynch task and the coherence to the 2-Hz AM.

Table 6.1.1. *Z*-scores in the BSynch task and in coherence at 0.5 Hz in the Natural speech task in electrodes T7 and T8 across testing times

	T1			**T2**			**T3**		
Subj	**BSynch**	**T7**	**T8**	**BSynch**	**T7**	**T8**	**BSynch**	**T7**	**T8**
1	-.39	-.76	-.37	-.57	.28	-.06	.25	.12	.43
2	-.33	.44	-.02	-	-	-	-.61	-.49	-.48
3	2.65	-.40	.93	-	-	-	-.67	3.62	3.39
4	-	-	-	-.53	-.55	-.76	-	-	-
5	.00	-.68	-.70	-.50	-.48	-.73	-	-	-
6	-	-	-	1.60	-.38	-.78	-	-	-
7	-	-	-	-.48	-.57	-.25	-.58	-.69	-.97
10	-	-	-	-	-	-	-.67	.18	.13
11	-.73	.31	1.65	-	-	-	-.80	.36	-.73
13	-.60	-.44	-.48	2.76	-.55	-.45	.56	-.54	-.71
15	-	-	-	-.68	-.52	-.42	-	-	-
16	-.69	-.62	-1.04	.80	-.23	.43	-	-	-
17	-.33	-.42	.87	-.35	-.18	-.42	1.27	-.17	.36
18	4.55	-.67	-.37	-	-	-	-	-	-
19	-	-	-	-.81	.14	-.02	-	-	-
20	-.34	.62	-.46	-.40	-.38	-.62	-	-	-

21	.05	-.22	.27	-.50	-.33	.14	-.41	-.30	.05
22	-	-	-	-.40	-.32	.29	-.83	-.66	-.37
23	-.43	-.70	-.13	-.81	.06	.01	-.55	-.23	-.72
24	.55	-.55	.28	-	-	-	-.59	-.57	-.92
25	.32	.42	-.76	2.67	-.52	.41	.57	.15	.19
26	-.68	-.44	-.09	-.78	-.51	-.12	1.29	-.60	.05
27	.24	-.36	-1.05	-	-	-	2.67	-.07	-.10
28	-	-	-	-.38	-.56	-.84	.10	-.70	-.61
29	-	-	-	-.79	1.74	1.02	-.64	.28	1.38
31	.37	-.38	-.75	-	-	-	-.46	-.21	-.82
32	-.30	2.20	-.29	.27	-.30	-.83	1.08	-.63	-.75
34	-.43	3.66	-.79	-.78	.77	.13	-.53	.70	.60
35	-.28	-.28	-.19	-	-	-	-	-	-
36	-.69	.31	.46	-.48	.69	1.53	-.90	.06	1.88
37	1.24	-.56	-.65	-	-	-	-.77	-.36	-.33
38	-	-	-	.52	-.55	-.16	-	-	-
39	1.53	-.65	-.71	-	-	-	-.60	-.45	.81
40	-.68	-.19	2.27	-	-	-	-.86	-.68	-.87
41	-.29	-.60	-.76	-	-	-	-.47	2.57	-.23
42	-.35	.96	2.88	-	-	-	-	-	-

Table 6.1.2. *Z*-scores in the BSynch task and in electrodes T7 and T8 for the coherence to the 2-Hz AM at T2 and T3

	T2			**T3**		
Subj	**BSynch**	**T7**	**T8**	**BSynch**	**T7**	**T8**
1	-.57	-.34	-.14	.25	-1.01	-1.04
2	-.28	-.06	-.55	-.61	-.86	.18
3	-	-	-	-	-	-
4	-	-	-	-.75	.39	.39
6	1.60	-.51	-.94	-	-	-
7	-	-	-	-.58	.17	-.39
9	-	-	-	.28	.38	1.75
10	-	-	-	-.67	1.56	2.56
11	-	-	-	-.80	-.04	-.16
13	2.76	-.12	1.18	.56	-.06	-.60
15	-.68	-.19	.09	.01	-1.08	-1.10
16	-	-	-	-	-	-
17	-.35	-.88	-.77	1.27	-.27	-.90

19	-.81	-.39	-.85	-	-	-
20	-	-	-	-.63	-.22	-.49
21	-.50	.84	-.03	-.41	-.25	.11
22	-.40	-.84	-.56	-.83	1.49	-.40
23	-.81	1.37	-.14	-.55	.19	-.97
24	-	-	-	-.59	-.64	.33
25	2.67	1.56	2.30	.57	-.92	.93
26	-.78	-.90	-.88	1.29	-.99	-1.11
27	1.76	-.24	-.52	2.67	-.77	-.63
28	-.38	.41	.71	.10	1.44	.38
29	-.79	-.47	-.79	-.64	-.54	-.95
31	-	-	-	-.46	-.97	-.92
32	.27	-.91	-.14	1.08	.02	-.60
34	-.78	-.04	.29	-.53	-.54	-.67
36	-.48	-.94	-.40	-.90	2.14	.93
37	-	-.09	1.02	-.77	3.11	2.00
38	-	-	-	2.51	-.66	.35
39	-	-	-	-.60	-.50	.75
40	-	-	-	-.86	-.44	-.47
41	.42	-.84	-.89	-.47	-.77	-.37
42	-	-	-	1.72	.43	.08

6.1.3.1. Coherence to Natural speech at 0.5 Hz and BSynch task

Scores in the BSynch task did not correlate significantly with values of coherence to Natural speech at 0.5 Hz in any of the testing times (see Table 6.1.3).

Table 6.1.3. Spearman partial correlations between the score in the BSynch task and the coherence to Natural speech at 0.5 Hz in electrodes T7 and T8 within T1, T2 and T3

		BSynch			
	Electrode	**Testing time**	**n**	ρ	p
Coherence 0.5 Hz	**T7**	**T1**	26	-.20	.34
	T8			-.12	.55
	T7	**T2**	22	-.31	.16
	T8			-.16	.48
	T7	**T3**	25	-.14	.49
	T8			.01	.97

6.1.3.2. Coherence to the 2-Hz AM

The complete results of the partial correlations between the BSynch task and the coherence values for the 2-Hz AM can be seen in Table 6.1.4. These showed that the only significant correlation was within T3. Coherence values in electrode T7 at T3 correlated negatively with performance in the BSynch task at T3, such that children with higher coherence to the 2-Hz AM in the left hemisphere performed worse in the behavioural rhythmic task within this phase. This inter-relation can be visualised in Figure 6.1.1.

Table 6.1.4. Spearman partial correlations between the score in the BSynch task and the coherence to the 2-Hz AM in electrodes T7 and T8 within T2 and T3. FDR correction is performed within testing time

			BSynch			
	Electrode	**Testing time**	**n**	***ρ***	***p***	**FDR-*p***
Coherence 0.5 Hz	**T7**	**T2**	19	-.13	.61	-
	T8			.19	.43	-
	T7	**T3**	30	-.50	.01*	.03*
	T8			-.29	.11	.17

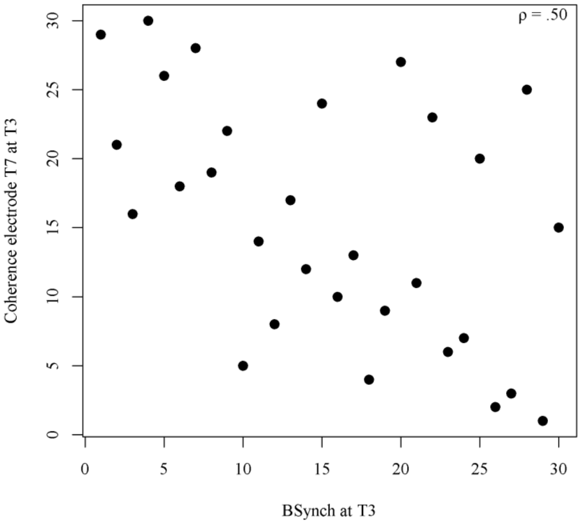

Figure 6.1.1. Partial correlation between the performance in the BSynch task and the coherence to the 2-Hz AM in electrode T7 within T3.

6.1.4. Discussion

This longitudinal Experiment evaluated behavioural and neural rhythm sensitivity at the delta band in early childhood to assess the comparability of these measures. Specifically, neural phase coherence to the slow temporal components of speech (0.5 Hz) and to signals amplitude-modulated (AM) at 2 Hz was directly compared with behavioural phase consistency in a tapping to a beat task (BSynch) at 1.67 Hz. Importantly, our study is the first to compare directly behavioural and brain phase consistency measures related to rhythm sensitivity. Our results showed that phase coherence to speech at 0.5 Hz did not correlate with behavioural performance. By contrast, coherence to the AM signal at 2 Hz correlated negatively with performance in the BSynch task only in electrode T7 and within our last testing time (T3). Overall, our results throw a cautionary note for studies using behavioural rhythm production measures as a proxy of underlying neural rhythmic sensitivity at the delta band, at least in terms of phase consistency and with the stimulation rate of the behavioural task we used.

Our hypothesis that coherence to speech at the delta band should be correlated with the BSynch task was based on a large corpus of evidence showing impaired rhythm sensitivity in the delta frequency range in dyslexia both with electrophysiological and with behavioural measures (Corriveau & Goswami, 2009; J. A. Hämäläinen et al., 2012; Molinaro et al., 2016; Power et al., 2016, 2013; Thomson & Goswami, 2008). Therefore, the absence of this correlation in our sample is maybe surprising. Nevertheless, no previous study had directly compared these measures. On the one hand, while previous studies using phase consistency of brainstem responses (cABRs) to the amplitude envelope of syllables had found a correlation with behavioural Beat synchronization (BSynch) performance at different frequencies within the delta range (Tierney & Kraus, 2013; Carr et al., 2014), the phase measure used in these studies is not comparable to the one we used in the current study (Skoe & Kraus, 2010). While the cABR explores the fidelity of the brainstem in reproducing the spectro-temporal features *within* the syllable (Chandrasekaran & Kraus, 2010), our measure explored phase coherence to the auditory stimuli across trials within the delta range (0.5 Hz). On the other hand, studies using phase measures more similar to ours (Colling et al., 2017) did not report results from a direct comparison between the neural response to a beat presented at 2.4 Hz and tapping performance at 1.2 Hz. Nevertheless, the results of this study in relation to reading are very similar to our own, since they showed that the neural response was related to reading achievement, such that dyslexics showed a difference in preferred phase as compared to controls, whereas tapping performance was not different between the groups. Similarly, we found that neural coherence to Natural speech was able to predict reading in our sample of typically developing children (Experiment 3), while our behavioural task was not (Experiment 4).

Regarding the AM signal at 2 Hz, our results are somehow puzzling. We found that children with larger coherence in T7 for the audio signal performed worse in the BSynch task at T3 (note that our sample size was very reduced at T2, and no consistent conclusions can therefore be drawn from this analysis). We did not find such relation for electrode T8. This result is difficult to interpret due to the lack of previous evidence, but it suggests that neural responses to periodic stimuli at delta rates might even be negatively correlated with behavioural performance in a rhythm production task at a similar rate (2 Hz *versus* 1.67 Hz). In any case, none of these measures predicted reading achievement in our sample at T3 (Experiments 3 and 4). Future studies might shed light into this relation, but overall our results suggest that behavioural performance in rhythm production tasks might not be as related to neural coherence measures as previously implied (Corriveau & Goswami, 2009; Goswami, 2011). In any case, due to our reduced sample size, we cannot discard that future studies with larger statistical power will find other significant relations in line with the previous literature.

Some aspects must be discussed regarding our analyses and stimulation rates. First, although the Rayleigh's test and the (neural) coherence measure test are both measures of phase consistency, they are not completely comparable due to the type of data used for the corresponding analyses. Our coherence measure is dependent of the amplitude of the EEG signal, while the amplitude parameter is irrelevant in the behavioural task. This aspect could have obscured similarities exclusively related to phase consistency between the tasks. Future analyses using measures that do not take into account the amplitude of the EEG signal such as phase-locking value (PLV) might reveal such similarities. Second, it is important to note that previous studies measuring rhythmic production with a tapping to a beat task in relation to reading have thrown different results depending on the rate of stimulation used, such that some studies have found that this behavioural task predicts reading performance (Lundetræ & Thomson, 2017; Carr et al., 2014), while other have not (Colling et al., 2017; Lundetræ & Thomson, 2017). For example, Lundetræ & Thomson (2017) found that introducing tapping performance at 1.5 Hz in pre-reading stages to a logistic regression predicting poor reading at the end of Grade 1 improved the model's classification power, while tapping at 2 Hz did not. These apparently subtle differences in the rate of stimulation within the delta range might hide relevant functional differences that would explain why we did not find a significant contribution of our tapping task to reading achievement (see discussion of Experiment 3, Chapter 4), and explain also the low theoretical consistency of the correlations between the BSynch task and our neural tasks. It is important to highlight that we do not believe that our results are excessively influenced by the motor component of the behavioural task, since the contribution of the motor dexterity component of rhythm synchronization tasks to the differences found between dyslexics and controls has been ruled out previously (Thomson & Goswami, 2008), and electrophysiological studies have shown that dyslexic children do not differ in their brain responses to movement-related beats (Colling et al., 2017).

Overall, the fact that all the tasks described here (coherence to Natural speech, coherence to 2-Hz AM BSynch) have received support from several studies in terms of their relation with reading (e.g. Corriveau & Goswami, 2009; J. A. Hämäläinen et al., 2012; Molinaro et al., 2016; Power et al., 2016; Carr et al., 2014) suggests that the relation between neural and behavioural measures might not be a matter of all or nothing. Indeed, further exploring the aspects discussed here (statistical tests and stimulation rate) might reveal a more straight relation between different measures of rhythm sensitivity, which we did not find with our current analyses, stimulation rates and sample size.

6.2. Conclusions of Chapter 6

Our aim with this chapter was to directly compare neural and behavioural measures of rhythm sensitivity in the delta frequency range. Our results revealed that performance in a behavioural rhythm synchronization task at 1.67 Hz and coherence to speech at 0.5 Hz did not correlate with each other. By contrast, we found a negative correlation between performance in the behavioural task and coherence to a signal amplitude-modulated (AM) at 2 Hz. Although these results might be tightly related to our stimulation rates and statistical tests, they throw a cautionary note on the use of behavioural and neural tasks of rhythmic sensitivity as exchangeable measures. This conclusion is supported by the results of our previous experiments, which showed that while coherence to speech at 0.5 Hz was able to predict reading performance, coherence to AM signals at 2 Hz and 4 Hz (Experiment 3) and behavioural rhythmic synchronization (Experiment 4) were not. The stimuli differences in terms of linguistic nature (verbal vs. non-verbal) and in temporal variability of the amplitude envelope (variable vs. non-variable) might be behind the mixed results found across our experiments, and these differences might be too prominent to equate the tasks. Finally, in any case, we cannot discard that our absence of results for these tasks is due to the lack of statistical power. Future studies with larger sample sizes might look in more depth into this issue.

Chapter 7: General discussion and conclusions

This doctoral thesis was aimed at exploring the contribution of rhythmic entrainment to reading acquisition. With that aim, we tested neural and behavioural rhythmic sensitivity prior to and after the introduction of formal reading instruction in children learning to read in Basque and examined their respective contribution to reading achievement.

This concluding chapter presents first a summary of our main findings in answer to our research questions (section 7.1). Later on, these findings are discussed in relation to multi-temporal resolution models of speech perception and associated accounts on the role of oscillatory temporal-sampling for reading development (section 7.2). This chapter concludes with a brief section of our main conclusions (section 7.3), to finally state the limitations of the current project (section 7.4) and possible directions for future research (section 7.5).

7.1. Summary of main findings: Answering our research questions

1. How does oscillatory activity in response to speech and to auditory stimuli modulated at rates relevant for speech perception develop during childhood? (Experiments 1 and 2, respectively)

The current work was the first study to show that the brain synchronises to the low-frequency components of speech (0.5 Hz) in terms of phase and to describe its longitudinal trajectory during early childhood (Experiment 1). The longitudinal progression of coherence to speech is characterised by an initially reduced left-hemispheric response, followed by extended bilateral activation across posterior sites of the scalp, to finally develop into a more bilateral focal temporal activation at the last time the children were tested (i.e. when they were 6-7 years old). Regarding oscillatory activity in response to signals amplitude modulated (AM) at the stress (2 Hz), syllabic (4 Hz) and phonemic (30 Hz) rates, our results showed that phase-synchronised activity at the stress rate was already established around the fifth year of life, and that it did not increase significantly after one year (Experiment 2). On the contrary, coherence to the syllabic rate of speech increased linearly as children developed (from approx. five to seven years old). We reported interesting lateralization patterns that will be discussed in depth in section 7.2.1 below. By contrast, we did not find significant coherence at high-frequency bands in any of the experiments across testing times.

2. What is the contribution of brain oscillatory activity to reading acquisition? (Experiment 3)

Right-lateralised coherence in response to Natural speech in temporal sites of the scalp in pre-reading stages (T2) predicted reading achievement one year later (T3). Moreover, the increase in coherence during this period (in which children received reading instruction for the first time) correlated negatively with reading achievement. By contrast, we could not show that coherence to the signals AM at the syllabic (4 Hz) and the stress (2 Hz) rates was significantly related to reading achievement, either transversally or longitudinally.

3. What is the contribution of rhythmic behavioural skills to reading readiness and later reading acquisition? (Experiment 4)

Behavioural rhythmic synchronization was tightly related to other reading predictors (i.e. phonological short-term memory, letter name knowledge and RAN) during pre-reading stages (T1 and T2). By contrast, it was not significantly related to other reading predictors or to reading itself once reading was acquired (T3).

4. Can we use brain and behavioural rhythmic sensitivity measures as *equivalent* for the prediction of reading achievement? (Experiment 5)

Our behavioural and neural tasks testing rhythmic entrainment at the delta band did not correlate significantly with each other, suggesting that, if related at all, their relation might depend tightly on the stimulation rates and on the statistical tests used to measure phase consistency.

7.2. Integration of results within current neurophysiological accounts of speech perception and reading development

Within this section, first we discuss our electrophysiological results within recent multi-temporal resolution models of speech (section 7.2.1). Later on, our electrophysiological and behavioural results are interpreted within an oscillatory temporal-sampling (TS) framework as a neurobiological basis for reading acquisition (section 7.2.2).

7.2.1. Multi-temporal resolution of speech in early childhood

Thanks to the longitudinal nature of the current work, we were able to examine independently the longitudinal trajectory of brain oscillatory activity, both in response to Natural speech (Experiment 1) and to amplitude-modulated (AM) signals at the stress (delta), syllabic (theta) and phonemic (gamma) rates (Experiment 2). This evidence is in itself revealing for the study of the anchoring processes of speech perception during childhood because of the high putative importance of synchronised brain activity for parsing the linguistic signal (e.g. Giraud & Poeppel, 2012). Furthermore, synchronised brain activity in terms of phase has been also related to core linguistic processes such as comprehension/intelligibility (e.g. Gross et al. 2013; Molinaro et al. 2018; Peelle et al. 2013) or the segregation of signals from a noisy background (Ding & Simon, 2012a; Vander Ghinst et al., 2016; Zion Golumbic et al., 2013).

Our experiments were theoretically framed within the study of brain mechanisms for the temporal resolution of the speech signal. In this line, it has been proposed that neural oscillations at the gamma (<30 Hz), theta (4-8 Hz) and delta (<4 Hz) bands synchronise respectively to the three predominant AMs of the linguistic signal occurring at this same rates and marking the progression of phonemes, syllables and stress, respectively (Giraud & Poeppel, 2012; Poeppel, 2003; Poeppel et al., 2008). This temporal alignment would modulate neural excitability so that meaningful spectral information in the linguistic signals falls within excitable moments of neurons allowing hence successful speech perception (Meyer, 2017; Peelle & Davis, 2012). Information coming from these different temporal scales has been suggested to occur through top-down modulation of the amplitude of higher-frequencies by the phase of the lower frequencies (i.e. phase-amplitude cross-frequency coupling; Giraud & Poeppel, 2012; Gross et al., 2013; Lakatos et al., 2005; Morillon et al., 2012). Within this theoretical line, hemispheric asymmetries have been proposed during the temporal resolution of the signal, such that right-lateralised brain oscillatory activity at low-frequency bands would code for the slow rhythms of speech (i.e. prosodic and syllabic information), whereas left-biased or bilateral high-frequency activity would code for fast phonemic contrasts (Boemio et al., 2005; Giraud & Poeppel, 2012; Poeppel, 2003; Poeppel et al., 2008). Moreover, while the discussion on the bilateral or left bias for phonemic information is still an open one (Boemio et al., 2005; Lehongre et al., 2013; Lizarazu et al., 2015), studies in infants and young children using NIRS or EEG power measures have supported the idea that right-hemispheric bias for processing the slow components of speech might be innate (Telkemeyer et al., 2009, 2011; Vanvooren et al. 2014).

Our findings provide only partial support to these theoretical accounts. On the one hand, we found coherence to speech in the delta band (0.5 Hz) and coherence to auditory signals AM at delta (2 Hz) and at theta (4 Hz) rates, suggesting that brain oscillatory activity at low-frequency bands is present since early childhood and might well be the mechanism through which the brain temporally parses the continuous speech signal for its spectral analysis (Giraud & Poeppel, 2012;

Poeppel, 2003). Nevertheless, our results in terms of lateralization do not coincide with the patterns suggested by previous accounts.

Regarding the developmental trajectory of brain-to-speech coherence (Experiment 1), we found that synchronised activity at the delta band (0.5 Hz) increased linearly across the years only in temporal *bilateral* electrodes (auditory cortices), while coherent activity in other sites of the scalp (mostly parietal) decreased or did not suffer significant changes, such that at T3 the only electrodes showing significant coherence to speech were electrodes T7 and T8. This suggests that coherence to speech follows a diffuse-to-focal trajectory, pattern that has been already shown for other language processes (Brown et al., 2005; Holland et al., 2001; Ressel et al., 2008). Future studies might examine in more detail the functional cognitive relevance of such trajectory.

Concerning the longitudinal course of AM signals (Experiment 2), our most prominent result is the fact that coherence to the delta band seems to be relatively stable in early childhood, such that there was no significant increase in coherence from our second testing time (T2) to our last testing time (T3). Here it is important to note that we found delta coherence to the 2-Hz AM rate to follow an interesting longitudinal course in terms of lateralization. While coherence was more prominent in right temporal sites of the scalp in T2, supporting multi-temporal resolution models that assign the right hemisphere a core role for processing the slow rhythms of speech (Giraud & Poeppel, 2012; Poeppel, 2003), we found no inter-hemispheric differences at T3. By contrast, coherence to signals modulated at the syllabic rate (4 Hz) increased linearly with age and was fully bilateral.

Overall in terms of lateralization, with the exception of a right-lateralization bias found for the stress rate (2-Hz AM) when children were five-to-six years old (T2), our results show that low-frequency activity was coded bilaterally across the testing times both in response to speech and to signals modulated at the stress and the syllabic rates. Importantly, as opposed to previous studies in infants and children measuring hemodynamic or electrical power responses, our study was the first to measure neural entrainment in young children using a phase coherence measure, a measure which is used across studies in adults to examine neural entrainment to the slow temporal components of speech (e.g. Bourguignon et al., 2013; Gross et al., 2013; Keitel et al., 2017; Peelle & Davis, 2012; Peelle et al., 2013). The neurobiological basis of hemispheric asymmetries for language processing is indeed a matter of ample debate (McGettigan & Scott, 2012), and contradictory lateralization patterns have been found previously in the literature. For example, when analysing theta-band phase coherence to syllables, some studies have reported larger activity in the right versus the left hemisphere (Abrams et al., 2008; Gross et al., 2013; J. A. Hämäläinen et al., 2012; Luo & Poeppel, 2007) while other studies have found left-lateralised responses to the syllabic envelope (4-7 Hz) of intelligible speech (Howard & Poeppel, 2012; Peelle et al., 2013). In our case, symmetric hemispheric oscillatory activity is difficult to interpret due to the lack of developmental evidence, but our results suggest that lateralization for language processing is a complex developmental process that interacts with age and linguistic experience (Telkemeyer et al., 2011). Moreover, we cannot discard that the linguistic profile of our participants (Basque-Spanish bilinguals) might also have played a role in the lack of inter-hemispheric differences, since bilinguals have been shown to process their native languages in a more bilateral manner as opposed to monolinguals (Hull & Vaid, 2007).

Importantly, we did not find significant coherence to speech at the theta band, replicating previous results in adults and children that only found coherence to speech in the delta band (Bourguignon et al., 2013; Power et al., 2016), but failing to provide evidence on adult-like syllabic envelope tracking in young children (Abrams et al., 2008; Howard & Poeppel, 2012; Peelle et al., 2013). By contrast, we did find coherence to the 4-Hz rate in the AMs experiment. The differential coherence patterns for the delta and theta bands as a function of the nature of the stimulus (linguistic vs. non-linguistic), together with the fact that we found different developmental trajectories of the bands in response to the 2- and 4-Hz AM signals, suggests that these bands might play a differential role in relation to language processing already since childhood. In this context, it has been proposed that the delta band would code for higher linguistic processes, while the theta band would reflect more basic auditory processes related to the low level acoustic features of the signal (Ding et al., 2016; Keitel et al., 2017; Meyer et al., 2016; Molinaro et al., 2016; Molinaro & Lizarazu, 2018; Vander Ghinst et al., 2016). Following these accounts, our evidence suggests that coherence to speech at the 0.5 Hz in children might also be related to processes related to language comprehension (e.g. syntactic grouping; Ding et al. 2016) as opposed to pure linguistic processing (see Meyer et al. 2017 for a discussion of this topic). Indeed, the direct comparison of delta activity in the AM experiment and the Natural speech experiment revealed that they were not correlated, suggesting that testing temporal auditory processing with these two paradigms might not be as similar as previously suggested (De Vos et al., 2017; J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Telkemeyer et al., 2011). Importantly, as mentioned above, the presence of linguistic information in the signal might trigger higher-order processes that would be also reflected in oscillatory activity in the delta band (Meyer, 2017). While listening to a linguistic signal, differentiating delta activity derived from pure acoustic envelope encoding from delta activity derived from higher linguistic processes is crucial if we want to establish a fine account on the comparability of linguistic *versus* non-linguistic stimuli. Until then, our results throw a cautionary note when using them in an exchangeable fashion.

Lastly, we found no coherence to speech in high-frequency bands (gamma range) either in response to speech or to the 30-Hz AM. We believe that this result is in line with previous theoretical accounts claiming that synchronization to the high frequencies should increase with age along with experience with fast phonemic processing, bootstrapped mainly by reading experience (Anthony & Francis, 2005; Morais et al., 1987; Ziegler & Goswami, 2005). Indeed, an increase in brain oscillatory responses to high-frequency bands has been reported both using power (De Vos et al., 2017) and coherence (Lizarazu et al., 2015) measures. An alternative explanation for the absence of coherence in higher frequencies could be that oscillatory activity in response to phonemic information has been mostly seen with amplitude measures (Giraud & Poeppel, 2012; Meyer, 2017; Poeppel et al., 2008), and phase coherence might have obscured relevant oscillatory activity at high rates.

Overall, our evidence for the development of oscillatory activity in the child brain highlights a differential developmental course of coherence as a function of two factors: the linguistic or non-linguistic nature of the stimulus and the target frequency band. These differences will most likely have relevant functional roles for speech perception, and in turn for reading acquisition. Future studies should strive to find such differential functional correlates.

7.2.2. Integration of our findings in an oscillatory temporal-sampling framework of reading acquisition

The *temporal sampling* (TS) theory offers a neurological basis that would account for both the phonological and rhythmic sensitivity deficits in dyslexia (Goswami, 2011, 2018). According to this, atypical (*misaligned*) neural entrainment to the low-frequency components of the amplitude envelope (AE) of speech would derive in inappropriate (or different) access to the spectral (phonemic) information of the linguistic signal occurring at fast rates, which would in turn lead to the phoneme-level processing deficits characteristic of dyslexia. At the same time, such atypical entrainment to the slow rhythms of acoustic signals would also explain their impaired performance in tasks requiring rhythmic sensitivity at low-frequencies (i.e. <10 Hz), both at the behavioural (Corriveau & Goswami, 2009; Thomson et al., 2006; Thomson & Goswami, 2008) and at the neural level (Abrams et al., 2009; J. A. Hämäläinen et al., 2012; Lizarazu et al., 2015; Molinaro et al., 2016). Supported by hemispheric asymmetries already highlighted by speech multi-temporal resolution models (e.g. Giraud & Poeppel, 2012), the TS theory proposes that the deficit of dyslexics would be localised in the right hemisphere, the hemisphere in charge of encoding information occurring at slow temporal rates (i.e. syllabic and stress rates), and there is evidence in favour of this (J. A. Hämäläinen et al., 2012; Molinaro et al., 2016).

Although most of the evidence supporting this theory comes from dyslexic populations, if right-hemisphere phase entrainment to the slow components of speech plays a causal role in the acquisition of phonological (and phonemic) skills, and in turn of reading, such relation should also be seen in normally developing children. Furthermore, if neural sensitivity to the temporal structure of speech components underlies both the development of phonological skills and behavioural rhythmic sensitivity, the ability of the brain to entrain to the slow temporal components of acoustic signals should also be reflected in performance in a behavioural rhythm synchronization task. Nevertheless, no previous study had tested the triple relation *neural entrainment-behavioural entrainment-reading* from a longitudinal perspective to test the prospective (causal) contribution of rhythmic sensitivity to future reading. Our longitudinal study was aimed at testing this relation. Our work was able to provide only partial support to the existence of such triple relation, such that neural entrainment to the slow components of speech (at 0.5 Hz) was related to reading development (Experiment 3), while coherence to rhythmic AMs (Experiment 3) and behavioural rhythmic synchronization were not (Experiment 4). Moreover, our neural and behavioural measures of rhythmic sensitivity were not consistently correlated to each other (Experiment 5).

From the neural perspective, our findings provide support for a causal role of right-hemisphere delta oscillatory activity in response to speech and the acquisition of future reading. In our sample of typically developing children, right hemisphere temporal coherence to speech in pre-reading stages (T2) significantly predicted reading performance one year later (T3). This result supports hence the TS and other theories assigning the right hemisphere a core role in tracking the slow amplitude changes of speech, that would in turn bootstrap the formation of appropriate phonological representations and reading (Goswami, 2011, 2018; Lallier et al., 2018, 2017). Interestingly, the increase of coherence from T2 to T3 (i.e. period at which children received reading instruction for the first time) correlated negatively with reading achievement at T3. This negative relation between the increase in brain oscillatory activity and reading achievement during the initial stages of reading acquisition has been previously reported in a longitudinal study using power measures, such that dyslexic readers showed a significantly larger increase in power responses to 20-Hz AM signals (beta band) as opposed to control readers (De Vos et al., 2017). We believe that our results are complementary to this since, based on phase-amplitude cross-frequency mechanisms (Canolty et al., 2006; Gross et al., 2013; Lakatos et al., 2005; Morillon et al., 2012), abnormal oscillatory activity at low-frequency bands in terms of phase (in line with the results we provide) would most likely lead to abnormal activity in high-frequency power sampling (De Vos et al., 2017).

By contrast, entrainment to the AM signals at the delta rate (2 Hz) was not significantly related to reading achievement in our experiment. This is at odds with previous evidence showing reduced activity in this frequency band in dyslexic adults (e.g. J. A. Hämäläinen et al., 2012). A possible explanation for the absence of this result could be our reduced sample size, or the fact that, as opposed to previous studies using AM stimuli, our participants were typically developing readers. More interestingly, the fact that we found a relation between reading and oscillatory tracking of the (pseudo-rhythmic) AE of speech at the delta band, while we did not find such relation for the (perfectly rhythmic) AE of the non-linguistic AMs suggests that to significantly capture the smaller variance in performance that characterises typical reading development it might be necessary to use temporally complex stimuli provided with verbal content such as natural speech (see Power et al., 2013 for a similar discussion). We believe that our mixed results could be the product of these two latter factors: the stimuli linguistic vs. non-linguistic nature and/or their different temporal complexity. On the one hand, the fact that the contribution of oscillatory activity to typical reading development might be mediated by the verbal nature of the natural speech stimulus is supported by the fact that we only found such contribution in the delta range, whereas we found no significant effects either in theta or in gamma activity. There is increasing evidence that delta activity in response to speech could also reflect higher-level linguistic processing (see Meyer, 2017 for a review), which suggests that the relation between reading and neural entrainment to speech at this band might not be *strictly acoustic*, but mediated by higher-order linguistic processes. It is hence possible that the contribution of delta entrainment to reading development is actually driven by these higher-order processes, and not merely by perceptual acoustic entrainment. On the other hand, the different predictive power of our tasks could have its origin in the fact that the AE of speech was not perfectly periodic, while the AE of the AMs was. If this were the case, the contribution of rhythmic sensitivity at delta frequencies could still be purely perceptual, but only visible in typical populations when using a temporally complex stimulus such as natural speech. To disentangle these accounts, future studies might compare signals with similar temporal complexity provided and deprived of linguistic content (e.g. natural speech *versus* vocoded speech) and examine their respective contribution to reading achievement.

We believe that our results for the behavioural rhythmic synchronization task at delta rates (1.67 Hz) could support and enrich this hypothesis, namely providing new information on the developmental trajectory of the reading-rhythm relation. The relation between the Beat synchronization (BSynch) task and reading-related skills changed across the testing times, such that scores in the rhythm task were correlated with performance in tasks measuring classical reading predictors such as letter name knowledge or phonological short-term memory in pre-reading stages (T1 and T2), while we could not replicate these correlations when children had already acquired reading (T3). In principle, we considered the possibility that the stimulation rate we used for the rhythm task could have obscured this relation, since the tempo used for the BSynch task seems to play a fundamental role when finding a relation between this and reading (Colling et al., 2017; Lundetræ & Thomson, 2017; Carr et al., 2014). Nevertheless, since the tempo of our BSynch task (and our statistical power) was the same across testing times, our stimulation rate cannot explain the different predictive power of the rhythm task across our testing times. This could suggest that the rhythm-reading relation might change with time as reading experience is acquired (Lundetræ & Thomson, 2017), and that this change could occur in at least two directions. On the one hand, in line with the argument outlined above, it could well be that this relation changes in terms of *rate*, such that beat rates that were predictive of reading readiness in pre-reading stages are not predictive of later reading, while other rates (untested in our experiment) might be. On the other hand, the rhythm-reading relation could change in terms of *quality*. In this line, it is possible that purely perceptual rhythmic synchronization tasks, both at the neural and at the behavioural level, are only predictive of performance in early stages of typical reading acquisition (i.e. in pre-readers or in very initial readers). In this sense, our results for the pre-reading stages (i.e. the relation between the BSynch task and the other classical reading predictors) confirm the idea that purely perceptual rhythmic sensitivity might have an important contribution in early decoding stages of the reading acquisition process, when reading is mainly based on letter-to-sound mapping (decoding) operations, in line with the proposal of the TS theory (Goswami, 2011, 2018). By contrast, our results for the reading stage (i.e. T3) suggest that, at least for typical reading, the importance of purely rhythmic sensitivity will decrease as the children acquire new reading strategies and reading start relying less on phonological skills, and more on higher-order linguistic aspects (Nagy et al. 2014). If that is the case, at later stages of the typical reading acquisition process (namely after the alphabetic or decoding phase is past), the rhythm-reading relation might be visible only when using stimulation provided of verbal information, such as natural speech. Future studies with more statistical power might seek to disentangle if the rhythm-(typical) reading relation is mediated by the presence of linguistic content, or if its nature is purely acoustic, as suggested by current theories on dyslexia (e.g. Goswami 2011; Lallier, 2017).

Lastly, with our evidence, we cannot conclude that behavioural rhythmic performance depends on the *quality* of neural entrainment to the slow components of speech, as previously suggested (Goswami, 2011, 2018), since the relation between our neural tasks and our behavioural task was not theoretically consistent. Further studies with larger statistical power are needed to draw definite conclusions on the relation between neural and behavioural rhythmic synchronization, especially regarding the optimal stimulation rates to capture such relation.

7.3. General conclusions

This doctoral thesis explored the contribution of rhythmic entrainment, both at the neural and at the behavioural levels, for reading acquisition. To our knowledge, the set of experiments that constitutes this work is the first to provide evidence for a longitudinal relation between low-frequency rhythmic entrainment and the acquisition of literacy in typically developing children prior and after receiving formal reading instruction.

Our results provide partial support to theories claiming that entrainment to the slow rhythms of speech might allow improved analysis of spectral information at faster rates (e.g. Giraud & Poeppel, 2012; Poeppel, 2003; Poeppel et al., 2008), and in turn lead to the formation of proper phonological representations and reading (Goswami, 2011, 2018; Lallier et al., 2018, 2017). Our longitudinal results on the lateralization of oscillatory activity in response to auditory stimuli suggest that low-frequency entrainment is a dynamic phenomenon that will interact with linguistic experience, and that further studies are needed to shed light on the functional meaning of such effects. Finally, regarding the contribution of delta-entrainment to reading acquisition, a possible interpretation of our results is that the delta rhythms-(typical) reading relation might change along development, such that purely perceptual rhythmic sensitivity might be intimately related to early phonological skills and reading readiness, while in later stages of the reading acquisition course (i.e. past the decoding/alphabetical phase), reading variance might be only captured by stimuli provided with verbal information and/or with a temporally complex structure.

7.4. General limitations

Our modest sample size is the most salient limitation of the current study. Although our initial sample size of forty-two children is not odd in the children literature, not all children completed all tasks within each testing time, and we lost participants along the years due to experimental mortality. This prevented us from implementing statistical techniques that require large parameters-to-observations ratios, such as structural equation modelling, which would have best modelled the indirect relations between our multiple variables to predict final reading achievement in our children.

Another caveat of the current project, which is otherwise common to longitudinal studies with children, is the large amount of time invested in testing. Taking into account that each child spent an average of three hours at the lab for each session, testing the children involved around 340 hours. There is no doubt that when implementing longitudinal designs, it is important to take into account the time-results trade-off. The electrophysiological part of our study was mostly exploratory, since brain coherence had never been tested in such young children. Accordingly, we settled for a rather small sample size as a first approach to the field -accepting the unfortunate fact that our behavioural tasks would also resent from this fact- in the hope that future studies with more statistical power will shed more light into the doubtlessly thrilling questions addressed in the current work.

It is also important to note that the children who participated in this study were Basque-Spanish bilinguals and that previous studies have reported differences in language activation between monolinguals and bilinguals (e.g. Hull & Vaid, 2007). Although language dominance was strictly controlled for in every analysis in the current work, we cannot discard that our findings regarding brain coherence, and especially the consistent bilateral pattern of activation, has something to do with the psycholinguistic profile of our participants. Unfortunately, we did not have a reliable measure of the *degree* of bilingualism of our children. Only future studies controlling for this measure or comparing directly coherence in monolinguals and bilinguals will be able to answer this question.

Due to time limitations, the data presented here does not represent the totality of the data that we collected from the children. For example, we also collected electrophysiological data in a task designed to evoke N170 responses to print to examine its relation with brain oscillatory activity at the different frequency bands and behavioural rhythmic entrainment. This would allow us testing the hypothesis that auditory and visual predictors of reading are related, and extend our conclusions to the multi-modal domain. Hopefully in the short-run, we will be able to analyse other datasets from the same children that will help us further unravelling the role of rhythmic entrainment for reading development.

Our analysis of the neural tasks was restricted to their contribution to reading (and phonological awareness) because of the mainly exploratory nature of this part of our project, while we were able to analyse the contribution of behavioural rhythmic skills not only to reading itself, but to reading readiness (i.e. the relation with other reading predictors). Testing the relation between neural entrainment and other behavioural reading predictors involved a too large number of comparisons (due to the multiple electrodes) for our modest sample size. In any case, we believe that these analyses would doubtless yield informative results on the particularities of the neural entrainment-reading relation, and we expect that future studies with larger sample sizes will be able to explore this aspect.

Regarding data analysis, besides the limitations imposed by our sample size, we believe that our coherence analyses would be best complemented by power analyses. This would give us the opportunity to replicate previous results on the contribution of high-frequency oscillatory activity to reading development (De Vos et al., 2017). Furthermore, it would allow us conducting cross-frequency coupling analyses that would help us disentangling the complex brain mechanisms that allow successful speech perception in early childhood, and compare it with previous evidence on such mechanisms in adults (Gross et al., 2013; Morillon et al., 2012). Lastly, coherence measures also have limitations. Coherence provides one single value across the entire time course of the experiment (e.g. one value in six minutes for our Natural speech experiment). Alternative measures that provide time-resolved estimates such as Time Response Function (TRF) could have been pursued. In the end, we opted for the measure used across most of studies for comparability reasons, but these alternatives would have provided more information on the dynamics of the responses over time. Furthermore, our analyses both for the behavioural and the neural task were restricted to phase dependency (or correlation), while measures of phase *preference* might also yield interesting results, as previously shown in the literature (e.g. Abrams et al., 2009; Power et al., 2013).

Finally, due to the young age of our participants at the first testing time, we used EEG, a technique with high temporal resolution but with important spatial limitations as compared to MEG. Our conclusions on the topography of our effects are hence limited at the level of the scalp, with the evident limitations that this carries along. Intense efforts to improve source-localization in EEG are yielding successful results (e.g. Lopes Da Silva, 2004), but time limitations prevented us from implementing such techniques on our own data. For a reliable reconstruction of the sources, we would have needed activity from ideally more than 64 electrodes and a T1 (MRI) of the participants. The young age of our participants prevented us from extending the testing sessions. Future studies will hopefully deal with this issue.

7.5. Future directions

Examining electrophysiological data from the time-frequency domain opens a precious window into the study of cognition, since the dynamics of oscillatory activity in the different frequencies could be a reflection of parallel processing for the resolution of complex cognitive tasks (Buzsáki, 2006). We believe that future studies in the reading field should make use of such possibility and explore the contribution of the orchestrated activity at different frequency bands (cross-frequency coupling) as a mechanism to integrate information at different temporal scales (phonemic, syllabic and prosodic). In order to proof the hypothesis that the acquisition of phonological awareness depends on appropriate perception of the slow rhythms of speech provided at the syllabic and the prosodic levels (Goswami, 2011, 2018; Lallier et al., 2018, 2017), it is necessary to provide evidence that the (power) activity of high-frequency bands, is modulated by the (phase) activity at low frequencies at initial stages of reading acquisition or even before reading is acquired. Results on brain oscillatory activity in terms of power (De Vos et al., 2017) or phase (our own results) are complementary, but studies should analyse both, and combine them, in order to draw definite conclusions about this issue.

Regarding the value of behavioural rhythmic entrainment to predict reading, the mixed results in the literature as a function of the stimulation rate used (Colling et al., 2017; Lundetræ & Thomson, 2017; Carr et al., 2014) suggest that this issue must be examined in depth. Future studies might find how the reading-rhythm relation changes along time and establish the optimal beat rate for the prediction of reading skills. Finding the precise cognitive correlates of rhythmic synchronization at different rates will help answering a challenging question, namely why do rhythmic skills at certain tempos predict reading, while others do not.

We also believe that cross-linguistic studies would provide the field with an invaluable insight on the role of rhythm for reading acquisition. Languages differ in their rhythmic structure (Ramus et al., 1999), and the results obtained in the different studies could be due to the characteristics of the language tested and hence not extendable to other languages (see Lallier et al., 2017 for an extense discussion of this issue).

Optimising the reading stage at which the children are tested is also an issue that requires the attention of future studies. Ideally, reading should be measured intensively during initial stages of formal reading instruction, and the children should be followed up until they are more advanced readers. Importantly, rather than fixing a schedule based on the children's age, the testing schedule should be adapted to the language orthography (transparent vs. opaque) to be able to best characterise the role of rhythm sensitivity at each of the stages that the children go through until reading is fully established. For example, in children learning to read in transparent orthographies such as Basque, the reading learning process (or at least the acquisition of decoding skills) is accelerated as compared to children learning to read in opaque orthographies such as English, and hence rhythmic sensitivity should be ideally tested short after reading is introduced in the school curriculum (e.g. November/December), once again in the middle of the school year (e.g. February/March) and again after the school end (e.g. June/July).

Future studies should also strive to discriminate oscillatory activity related to pure acoustic processing from activity related to higher-order linguistic operations, especially in the delta band, in order to conclude if the oscillatory activity that we measure with non-linguistic stimulation (e.g. amplitude-modulated signals) can be compared to the oscillatory activity in response to linguistic stimulation. Such discoveries would maybe help understanding the origins of the mixed evidence on the contribution of the different frequency bands to the phonological disorder of dyslexic individuals.

Last but not least, the ultimate goal of the studies examining reading acquisition should always be the prevention and remediation of developmental reading disorders. Behavioural rhythmic training programs are already giving acceptable results in improving phonological awareness in children (Bhide et al., 2013; Degé & Schwarzer, 2011; Slater et al., 2014). By contrast, the efficacy of programs training *neural sensitivity* to speech for the improvement of phonological skills is yet unknown, since no such program has been yet implemented. Proving that, in our opinion, would be the *litmus test* for current theoretical accounts assigning the perception of slow rhythms of speech a core role in the development of phonological awareness and subsequent reading (Goswami, 2011; Lallier et al., 2018).

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Appendix

A1. Language dominance (Chapter 3)

Three measures were used to assess children's language dominance: a Language questionnaire, a short interview supported by the experimenter's subjective assessment and an objective expressive vocabulary measure.

1. Language questionnaire

We used mainly three items of a standardised children questionnaire used at BCBL to assess language dominance during childhood: the child's *preferred* language, percentage of exposure to Spanish/Basque and age of acquisition (AoA) of Spanish/Basque, all as reported by the parents/tutors.

2. Short interview and experimenter's subjective assessment

The experimenter asked the child which language she/he thought she/he was better at, and also which language did she/he talk to with his close family and school friends. Moreover, she took note of the language in which the child expressed himself/herself spontaneously.

3. Objective vocabulary measure

The expressive vocabulary subtest of the BEST was used to obtain an objective measure of language dominance. The children saw a total of 39 images, one at a time, in a computer screen. Pictures were coloured, child-friendly images depicting common substantives varying in difficulty. The children's task was to name the pictures. The next picture was only presented after the child emitted a response, and accuracy scores were recorded (maximum score 39). Children completed the Basque and the Spanish versions of the task with the order counterbalanced across participants (i.e. half of the children completed first the Basque version and half of the children, the Spanish version). Both language versions included, this task took approximately eight minutes.

The individual scores for the children in these three measures and final decision on the child's language dominance are provided in Table A1.1. Across-years test-retest reliability of the BEST task was assessed through pair-wise Spearman correlations controlling for children's age and IQ. The BEST scores correlated significantly at T1 and T2 (ρ = .70; *p* <.001), at T2 and T3 (ρ = .80; *p* <.001), and at T1 and T3 (ρ = .56; *p* <.01). Since the questionnaire and the short interview (Q+I, thereafter) measures did not change significantly across the years, only the data collected at T1 were used. When the Q+I did not coincide with the BEST (five cases), the Q+I measure was used to define language dominance. This was done so because the Basque Country is a community where Spanish and Basque vocabularies are in constant contact, but where lexical transfer from Spanish to Basque is notably larger than in the opposite direction (e.g. Murillo, 2008). Note that, supporting this, contradictory results between Q+I and the BEST always happened in one direction: the Q+I suggested Basque dominance, while the BEST score in Spanish was higher than the score in Basque (see subjects marked with an * in Table A1.1). Therefore, it was likely that, although the dominant language of the child was Basque, his/her vocabulary for the specific items used in the BEST was larger in Spanish because of Spanish-to-Basque lexical interference.

Table A1.1. Children's data on the three different dominance language measures. The last column provides the language dominance of the particular child, as estimated from these three measures.

	Q+I						**BEST**						
		Exposure (%)			**AoA**								
Subj	**Interview**	**BS**	**SP**	**Other**	**BS**	**SP**	**BS T1**	**SP T1**	**BS T2**	**SP T2**	**BS T3**	**SP T3**	**Dom**
1	SP	35	60	5	0	0	23	26	28	34	30	37	SP
2	BS	70	30	0	0	0	27	13	33	22	38	19	BS
3	BS	70	25	5	0	0	30	27	32	35	35	33	BS
4	SP	34	65	1	0	0	9	20	13	26	-	28	SP
5	SP	40	50	10	2	0	-	24	-	28	-	-	SP
6	BS	70	30	0	0	0	30	27	24	30	28	32	BS
7	SP	45	50	5	2	0	25	25	15	28	18	33	SP

8	SP	20	80	0	2	0	8	36	-	-	-	-	SP
9	BS	65	30	5	2	2	-	19	21	29	28	31	BS*
10	BS	70	30	0	0	0	29	29	34	30	34	35	BS
11	BS	80	20	0	0	0	31	30	36	35	32	36	BS
12	BS	80	20	0	0	2	26	-	30	12	-	-	BS
13	BS	60	35	5	0	0	21	25	23	29	24	31	BS*
14	BS	80	20	0	0	2	25	-	26	-	-	-	BS
15	SP	25	70	5	2	0	24	-	24	31	27	34	SP
16	BS	80	20	0	0	0	30	20	36	25	33	30	BS
17	BS	70	25	5	0	2	32	10	33	12	34	26	BS
18	BS	70	25	5	2	0	34	9	-	-	-	-	BS
19	BS	80	20	0	0	0	29	19	32	21	-	-	BS
20	BS	70	20	10	0	0	18	19	19	26	21	29	BS*
21	BS	85	10	5	0	2	28	4	35	13	23	34	BS
22	SP	40	60	0	0	2	-	14	25	20	23	24	SP
23	SP	40	50	10	0	0	17	37	19	37	21	37	SP
24	SP	50	50	0	0	0	26	33	30	33	28	36	SP
25	BS	80	20	0	0	0	34	26	36	31	36	34	BS
26	BS	90	10	0	0	4	26	8	27	21	32	20	BS
27	BS	75	20	5	0	3	23	28	28	34	33	33	BS*
28	BS	75	20	5	0	0	27	22	31	30	32	32	BS
29	BS	80	20	0	0	0	25	-	27	-	32	13	BS
30	BS	50	45	5	0	0	34	11	-	22	-	-	BS
31	BS	90	10	0	0	4	29	8	30	23	34	17	BS
32	BS	70	25	5	0	3	26	28	31	31	33	35	BS*
33	BS	85	10	5	0	4	30	19	-	-	-	-	BS
34	BS	90	10	0	0	0	24	16	25	25	21	30	BS
35	BS	80	20	0	0	0	23	19	-	-	-	-	BS
36	BS	90	8	2	0	0	12	13	36	12	38	33	BS
37	SP	25	70	5	0	0	14	32	16	33	14	35	SP
38	BS	80	15	5	0	2	32	26	35	31	36	32	BS

39	SP	40	60	0	2	0	16	34	23	34	15	37	SP
40	BS	60	35	5	0	2	31	28	-	29	31	39	BS
41	SP	50	45	5	1	0	24	33	29	36	31	37	SP
42	SP	35	60	5	0	0	19	31	-	35	27	37	SP

Subj = Subject; BS = Basque; SP = Spanish; Q+I = Questionnaire + Interview; AoA = Age of acquisition; Dom = Language Dominance

* Children for whom the scores in the Q+I measure did not match their BEST scores

A2. Relation between reading and coherence in parietal electrodes (Experiment 3, Chapter 4)

A2.1. Spearman correlations between reading and coherence to Natural speech at 0.5 Hz in parietal electrodes

Table A2.1. Partial Spearman correlations between reading achievement at T3 and the different measures of coherence to Natural speech at 0.5 Hz in parietal electrodes across testing times

a. Raw coherence

			Reading T3		
	Electrode	**Testing time**	**n**	***ρ***	***p***
Raw coherence	P7	T1	22	-.14	.54
	P8			.18	.43
	P7	T2	25	.32	.12
	P8			.16	.45
	P7	T3	24	.16	.45
	P8			.18	.38

b. CI

		Reading T3		
	Electrode	**n**	***ρ***	***p***
CI_{13}	P7	20	.25	.28
	P8		.17	.48
CI_{23}	P7	19	-.19	.44
	P8		.16	.50

CI = Change index

c. LI

		Reading T3		
	Testing time	**n**	***ρ***	***p***
LI	T1	22	-.08	.72
	T2	25	.06	.78
	T3	24	-.20	.35

LI = Lateralization index

A2.2. Spearman correlations between reading and coherence to amplitude modulations (AMs) at 2 and 4 Hz in parietal electrodes

Table A2.2. Partial Spearman correlations between reading achievement at T3 and the different measures of coherence in parietal electrodes across T2 and T3 for the 2-Hz AM

a. Raw coherence

			Reading T3		
	Electrode	**Testing time**	**n**	***ρ***	***p***
Raw coherence	T7	T2	24	-.12	.58
	T8			-.08	.71
	T7	T3	30	.01	.96
	T8			-.18	.35

b. CI

		Reading T3		
	Electrode	**n**	***ρ***	***p***
CI$_{23}$	P7	23	-.08	.72
	P8		-.02	.92

CI = Change index

c. LI

		Reading T3		
	Testing time	**n**	***ρ***	***p***
LI	T2	24	.18	.40
	T3	30	.18	.33

LI = Lateralization index

Table A2.3. Partial Spearman correlations between reading achievement at T3 and the different measures of coherence in parietal electrodes across testing times for the 4-Hz AM

a. Raw coherence

			Reading T3		
	Electrode	**Testing time**	**n**	***ρ***	***p***
Raw coherence	P7	T1	20	-.06	.82
	P8			-.06	.82
	P7	T2	24	-.16	.45
	P8			-.12	.54
	P7	T3	30	-.22	.30
	P8			-.15	.44

b. CI

		Reading T3		
	Electrode	**n**	***ρ***	***p***
CI$_{13}$	P7	19	-.01	.97
	P8		-.39	.10
CI$_{23}$	P7	23	.05	.81
	P8		-.04	.85

CI = Change index

c. LI

		Reading T3		
	Testing time	**n**	***ρ***	***p***
LI	T1	20	.14	.56
	T2	24	.11	.61
	T3	30	.34	.09

LI = Lateralization index

A3. Relation between coherence to Natural speech at 0.5 Hz in temporal electrodes and phonological awareness at T3 (Experiment 3, Chapter 4)

The coefficient of the Spearman ranked correlation between the Reading composite measure and the Phoneme deletion/elision task (ρ = .47; p <.01) was highly significant. Accordingly, the relation between reading and phonological awareness was considered to be acceptable in our sample. The coefficients for the Spearman correlations between the different coherence measures at 0.5 Hz and phonological awareness (as measured via the task Phoneme deletion/elision) are shown in Table A3.1.

Table A3.1. Partial Spearman correlations between phonological awareness at T3 and the different measures of coherence to Natural speech at 0.5 Hz in temporal electrodes across testing times

a. Raw coherence

			PhDel T3		
	Electrode	**Testing time**	**n**	***ρ***	***p***
Raw coherence	T7	T1	22	-.38	.09
	T8			.10	.65
	T7	T2	25	.26	.21
	T8			.27	.18
	T7	T3	24	-.14	.53
	T8			-.34	.10

PhDel = Phonological deletion/elision

b. CI

		PhDel T3			
	Electrode	**n**	***ρ***	***p***	**FDR-*p***
CI$_{13}$	T7	20	.19	.42	.63
	T8		.52	.02*	.06
CI$_{23}$	T7	19	-.02	.95	.95
	T8		.57	.01*	.06

PhDel = Phonological deletion/elision; CI = Change index

c. LI

		PhDel T3		
	Testing time	**n**	***ρ***	***p***
LI	T1	22	-.37	.09
	T2	25	-.16	.46
	T3	24	.19	.38

PhDel = Phonological deletion/elision; LI = Lateralization index

A4. Behavioural battery (Experiment 4, Chapter 5)

This section presents the *z*-scores of the children in the tasks measuring classical reading predictors (Table A4.1). Thereafter, we present the partial Spearman correlations among the tasks within each testing time (Table A4.2) and across the testing times (Table A.4.3). Finally, Table A4.4 presents the results of the partial correlations between the classical predictors across testing times and Reading at T3. For parsimony reasons, the abbreviations used for the name of the tasks are only specified in Table A4.1.

Table A4.1. *Z-s*cores of the children in the tasks measuring reading predictors across testing times

	LNK		**RAN**			**PWRep**			**DSB**	**PhDel**
Subj	**T1**	**T2**	**T1**	**T2**	**T3**	**T1**	**T2**	**T3**	**T3**	**T3**
1	.74	.75	-.77	-.42	-.47	1.22	.99	1.39	-.40	1.05
2	.25	-.16	-.12	-.46	-.82	-1.04	.75	-1.08	.31	1.05
3	1.24	.75	-.73	-.90	-.54	1.21	1.03	1.30	1.75	1.05
4	-1.24	-1.37	1.45	4.03	-	-1.63	-2.50	-1.21	-.40	-.83
5	-.08	-	-	.57	-	-.68	-.66	-	-	-
6	.91	.14	-.69	-	-.54	-.98	1.35	.10	.31	.42
7	-2.40	-4.09	3.90	.60	2.25	-2.06	-1.33	-.29	-	-1.46
8	.08	-	-.33	-	-	-.66	-	-	-	-
9	.08	.75	-	-.63	-.54	-.35	-1.66	.01	1.75	.74
10	1.24	.75	-.51	.03	-.58	.03	.39	.27	.31	-.52
11	1.24	.75	-.46	-.15	-	1.42	.88	.70	-1.12	.74
12	.41	-.46	-.38	-.82	-	-.90	.00	-	-	-
13	-1.57	.45	-.17	-.32	-.84	.10	.31	.80	1.03	.74
14	.25	-.46	-.35	-.02	-	-2.28	-.67	-	-	-
15	-1.57	.14	1.54	.26	.54	.24	.59	.49	-1.12	-.20
16	.08	.14	-.93	-.72	-.50	-.79	-	-.83	.31	.74
17	-1.40	-.76	.01	.92	.59	-.75	-.70	-.67	.31	-.20
18	1.07	-	-1.16	-	-	.34	-	-	-	-
19	-.74	-1.97	-1.27	-1.05	-	.00	.78	-	-	-
20	-.25	.14	.49	-.23	-.18	-1.27	-1.59	-2.26	-1.12	-2.08
21	-.08	.14	-.76	-.37	-.93	.46	1.01	2.34	-1.12	.11
22	-.91	-.76	-	1.83	1.86	-.13	-.21	-1.69	-1.12	-
23	-1.57	-.76	-.19	.67	1.15	1.21	1.04	.17	2.47	.74
24	.91	.75	-.79	-.97	-.75	.98	.67	.80	1.75	1.05
25	1.07	.75	-.68	-.80	-.60	.36	-.75	-.90	-.40	.42

26	.74	.45	1.01	.59	.63	-.15	.31	-.69	1.03	-
27	.74	.75	-.66	-.35	1.89	.77	.18	.79	.31	-1.46
28	-.41	-.16	.72	.32	-.14	.24	.85	.19	-.40	-.83
29	-	-1.07	.79	-1.18	-.93	-	-	-1.98	-1.12	-.20
30	.41	.45	-.39	-	-	.70	-1.39	-	-	-
31	.25	.75	-.21	.11	-.44	1.69	1.01	-.03	.31	1.05
32	1.24	.75	-.56	-1.03	-1.01	-.90	-.06	.39	.31	.11
33	.58	-	-.71	-	-	.79	-	-	-	-
34	-1.40	-	.49	.99	.17	-.34	-2.04	-.91	.31	-1.46
35	.25	-	.28	-	-	.31	-	-	-	-
36	.74	.75	-.46	-.31	-.77	-.50	-.39	.11	-.40	.42
37	1.07	.75	-.33	.06	.48	.10	-.05	.42	-1.12	.42
38	.58	.75	.39	-.85	-1.23	.93	.85	.62	-.40	.42
39	-1.40	-.46	1.17	.84	2.05	1.30	.32	.53	-1.12	-1.14
40	-.58	-.46	-1.03	-	-.83	.88	-.78	.80	-.40	1.05
41	.91	.75	.62	-.20	-.09	1.40	1.01	-.40	.31	.42
42	-1.40	.45	-.18	-	1.14	.44	.45	.73	-1.12	-2.40

PWRep = Pseudoword repetition; PhDel = Phoneme deletion/elision; DSB = Digit span backward

Table A4.2. Partial Spearman correlations between the reading predictors within testing time

a. T1

		T1			
		PWRep		**LNK**	
		n	***ρ***	**n**	***ρ***
T1	**RAN**	39	.16	38	-.51***
	PWRep	-		41	.17

*** *p* <.001; ** *p* <.01; * *p* <.05; ˙ *p* <.10

b. T2

		T2			
		PWRep		**LNK**	
		n	***ρ***	**N**	***ρ***
T2	**RAN**	32	-.26	32	-.37*
	PWRep	-		34	.25

*** *p* <.001; ** *p* <.01; * *p* <.05; ˙ *p* <.10

c. T3

		T3					
		PWRep		**PhDel**		**DSB**	
		n	***ρ***	**n**	***ρ***	**n**	***ρ***
T3	**RAN**	31	-.21	29	-.55**	30	-.12
	PWRep	-		31	.19	32	.11
	PhDel	-		-		30	.52**

*** *p* <.001; ** *p* <.01; * *p* <.05; ˙ *p* <.10

Table A4.3. Partial Spearman correlations among the reading predictors across testing times

		T2						**T3**							
		RAN		**PWRep**		**LNK**		**RAN**		**PWRep**		**PhDel**		**DSB**	
		n	***ρ***	**n**	***ρ***	**n**	***ρ***	**n**	***ρ***	**n**	***ρ***	**n**	***ρ***	**n**	***ρ***
T1	**RAN**	31	60***	33	-.26	34	-.26	29	.49***	31	-.49**	30	-.57***	30	-.34˙
	PWRep	33	-.003	36	.58***	35	.36*	30	.007	32	.58***	30	.38*	31	.01
	LNK	33	-.57***	36	.28	35	.70***	30	-.46**	32	.16	30	.48**	31	.17
T2	**RAN**	-						28	.83***	30	-.19	28	-.50**	29	.18
	PWRep							29	-.16	31	.57***	29	.45*	30	.62***
	LNK							30	-.47**	32	.35*	30	.41*	31	.28

*** *p* <.001; ** *p* <.01; * *p* <.05; ˙ *p* <.10

Table A4.4. Partial Spearman correlations between the reading predictors across the years and the Reading composite at T3

		Reading composite T3	
		n	***ρ***
T1	**RAN**	31	-.58***
	PWRep	32	.28
	LNK	30	.34˙
T2	**RAN**	30	-.31˙
	PWRep	31	.19
	LNK	32	.35*
T3	**RAN**	31	-.36*
	PWRep	33	.26
	PhDel	31	.47**
	DSB	32	.37*

*** *p* <.001; ** *p* <.01; * *p* <.05; ˙ *p* <.10

A5. Synchronisers vs. Non-synchronisers at T2: analysis without subject 21 (Experiment 4, Chapter 5)

The results of the Mann-Whitney tests and non-parametric ANCOVAs examining the effect of the Group at T2 on performance in the reading predictors at T2 without the possible longitudinal outlier (subject 21) confirmed that these did not change (see Table A6.1) as compared to the main analysis (see table 5.1.7 in main text).

Table A5.1. Results of the non-parametric tests comparing performance in the tasks measuring the reading predictors at T2 as a function of group belonging (Synch vs. Non-synch) at T2 without subject 21

	Mann-Whitney		**(n-p) ANCOVA**	
	U	***p***	***h***	***p***
LNK T2	37.5	.02*	3	.03*
RAN T2	121	.03*	2.96	.06

n-p = non-parametric