



**Amodal atypical neural oscillatory activity in dyslexia: A cross-linguistic perspective.**

Journal:	<i>Clinical Psychological Science</i>
Manuscript ID	CPX-14-0170.R4
Manuscript Type:	Theoretical/Methodological/Review Article
Date Submitted by the Author:	27-Aug-2016
Complete List of Authors:	Lallier, Marie; BCBL. Basque Center on Cognition, Brain and Language, Molinaro, Nicola; BCBL. Basque Center on Cognition, Brain and Language; Ikerbasque Lizarazu, Mikel; BCBL. Basque Center on Cognition, Brain and Language, Bourguignon, Mathieu; BCBL. Basque Center on Cognition, Brain and Language Carreiras, Manuel; BCBL. Basque Center on Cognition, Brain and Language; Ikerbasque; Universidad del Pais Vasco, Departamento Lengua Vasca y Comunicación
Keywords:	Dyslexia, Neural oscillations, Reading development, Cross-linguistic, Auditory and visual processing
Abstract:	It has been proposed that atypical neural oscillations in both the auditory and the visual modalities could explain why some individuals fail to learn to read and suffer from developmental dyslexia. However, the role of specific oscillatory mechanisms in reading acquisition is still under debate. Here, we take a cross-linguistic approach and argue that both the phonological and orthographic specifics of a language (e.g., linguistic rhythm, orthographic depth) shape the oscillatory activity that contributes to reading development. The proposed theoretical framework should allow future research to test cross-linguistic hypotheses that will shed light on the heterogeneity of auditory and visual disorders and their underlying brain dysfunction(s) in developmental dyslexia.

SCHOLARONE™  
Manuscripts

1  
2  
3 **Amodal atypical neural oscillatory activity in dyslexia: A cross-linguistic perspective.**  
4  
5  
6

7 Marie Lallier<sup>1</sup>, Nicola Molinaro<sup>1,2</sup>, Mikel Lizarazu<sup>1</sup>, Mathieu Bourguignon<sup>1</sup> & Manuel  
8  
9 Carreiras<sup>1,2,3</sup>  
10  
11  
12  
13

14 1 BCBL. Basque Center on Brain Cognition and Language, Spain  
15

16 2 Ikerbasque. Basque Foundation for Science. Bilbao, Spain.  
17

18 3 Departamento Lengua Vasca y Comunicación. UPV/EHU. Bilbao, Spain.  
19  
20  
21  
22  
23  
24  
25  
26

27 **Keywords:** Dyslexia, Neural Oscillations, Reading Development, Cross-linguistic, Auditory  
28  
29 and visual processing  
30  
31  
32  
33  
34  
35

36 Address correspondence to:  
37

38 Basque Center on Cognition Brain and Language  
39

40 Paseo Mikeletegi 69, planta 2  
41

42 20009 Donostia-San Sebastian  
43  
44

45 Spain  
46

47 Email: [m.lallier@bcbl.eu](mailto:m.lallier@bcbl.eu)  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 Developmental dyslexia (dyslexia, hereafter) is a case of reading failure that affects 3 to 10%  
4 of the population and where literacy skills are specifically delayed despite normal  
5 intelligence, the absence of psychiatric and sensory disorders, and appropriate schooling.  
6  
7 Dyslexia is generally associated with phonological (oral language) difficulties which are  
8 thought to explain grapheme<sup>1</sup>-to-phoneme conversion deficits (Ramus et al., 2003) although  
9 this is not always the case (see Bosse, Tainturier, & Valdois; Lallier, Thierry, & Tainturier,  
10 2013). The present article will focus on the hypothesis that the core difficulties in dyslexia  
11 reside in atypical neural oscillations. Also, we propose that differences between languages  
12 might explain part of the current puzzling heterogeneity characterizing the sensory  
13 manifestations of dyslexia (Lallier & Valdois, 2012; Protopapas, 2012; Ramus & Ahissar,  
14 2012). Accordingly, we will further argue for the necessity to take a cross-linguistic approach  
15 for studying the amodal oscillatory deficits in dyslexia.

16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Until now, most of the available cross-linguistic work has focused on orthographic variations between languages on grapheme-to-phoneme conversion regularity (Landerl et al., 2012; Ziegler & Goswami, 2005). However, and despite the consensus that developmental dyslexia stems from a phonological *auditory* deficit (i.e., deficits tapping into oral language abilities), little research has examined the influence of auditory linguistic experience on reading acquisition. Still, languages clearly differ on their phonological structures and the importance of different auditory cues.

The present cross-linguistic framework aims (i) to deepen our understanding of the causes of dyslexia, since its etiology should overlap between languages, and (ii) to refine the alternative theories that propose oscillatory neural activity as determinants of reading development trajectories (e.g., Giraud & Ramus, 2013; Goswami, 2011). In order to do so, differences between languages on their phonological (linguistic rhythms, phonotactics) and

---

<sup>1</sup> A definition of the underlined terms in the text is provided in the Appendix.

1  
2  
3 orthographic (orthographic depth) role for the acquisition of reading should be systematically  
4  
5 defined and quantified. This new approach could allow researchers to formulate predictions  
6  
7 at the neural, cognitive, and sensory levels of signal analysis, in both the visual and auditory  
8  
9 domains, to account for the heterogeneity of dyslexia, taking into account cross-linguistic  
10  
11 differences between monolingual populations as well as within bilingual individuals.  
12  
13 Moreover, it should help clinicians to interpret more accurately the cognitive and reading  
14  
15 deficits associated with dyslexia in light of the linguistic background of their patients.  
16  
17  
18  
19

### 20 21 **1. Heterogeneity of the sensory symptoms in dyslexia: a multi-temporal resolution** 22 23 **approach across modalities** 24 25

26  
27 Dyslexia is a heterogeneous disorder which can manifest itself differently at the behavioural  
28  
29 (e.g., word *versus* pseudoword - letter sequence that looks like a real word in a language but  
30  
31 isn't one - reading difficulties; Zoubrinetzky, Bielle, & Valdois, 2014), cognitive (e.g.,  
32  
33 phonological *versus* visual attention disorders subtypes; Bosse et al., 2007), and biological  
34  
35 (e.g., inferior frontal gyrus *versus* parietal lobe dysfunctions subtypes; Peyrin et al., 2012)  
36  
37 levels. Here, we hypothesize that this heterogeneity is reflected at the sensory level of  
38  
39 processing (visual and auditory modalities in particular) and that it can be explained by the  
40  
41 fact that two temporal scales for auditory and visual processing may contribute, relatively  
42  
43 independently, to oral and written language development (see section 4 for further discussion  
44  
45 on the heterogeneity of dyslexic subtypes). This idea supports the hypothesis of a 'multi-  
46  
47 temporal resolution sensory processing deficit' in dyslexia that would explain why some  
48  
49 dyslexic subtypes could *preferentially* manifest themselves in difficulties for fast temporal  
50  
51 sensory processing, whereas others would be more visible when processing slow temporal  
52  
53 sensory stimuli (Lallier & Valdois, 2012, for a review). Previous theories of dyslexia have  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 offered explanations why problems at each of these two time scales in both the auditory and  
4  
5 the visual modalities can have an impact on the development of reading skills.  
6

7 First, the sluggish attentional shifting theory (Hari & Renvall, 2001) posits that  
8  
9 dyslexia results from problems in disengaging attention automatically from the attended  
10  
11 segments of speech or orthographic sequences, impeding the formation of both phonological  
12  
13 and orthographic representations. The impaired amodal mechanism would affect the  
14  
15 “relatively” slow temporal encoding (e.g., occurring approximately every 100–200 ms) of  
16  
17 salient anchors in perceptual sequences that are essential to guide the shifts of the attentional  
18  
19 focus for an optimal analysis. In the auditory modality, sluggish attentional shifting was  
20  
21 proposed to reflect the atypical entrainment to syllabic stress and speech rhythm (Goswami,  
22  
23 Huss, Mead, Fosker, & Verney, 2013; Lallier, Donnadieu, & Valdois, 2013). In the visual  
24  
25 modality, sluggish attentional shifting might cause inadequate saccades towards the optimal  
26  
27 viewing position in letter sequences (Hari & Renvall, 2001). These authors proposed that  
28  
29 neurobiological bases of this attentional disorder might reside in a dysfunction of the  
30  
31 temporo-parietal junction, which could possibly be secondary to a magnocellular deficit.  
32  
33  
34  
35

36 Second, Stein and Talcott (1999) proposed that an amodal impairment at processing  
37  
38 ‘transient’ fast temporal changes is the core deficit in dyslexia, and is directly caused by the  
39  
40 dysfunction of the magnocellular system. This deficit might be preferentially associated with  
41  
42 difficulties in encoding phonemic and graphemic units: in the auditory modality, a magnocell  
43  
44 dysfunction would specifically affect the encoding of rapid speech features that distinguish  
45  
46 phonemes in a given language (e.g., Tallal, 1980); in the visual modality, the hypothesis  
47  
48 predicts impaired control of ocular movements, in particular unstable binocular fixation, that  
49  
50 would lead to visual confusion, superposition, and distortion of letters during reading (Stein,  
51  
52 2001). Some authors further proposed that fast (~40 stimuli per second) visual serial scanning  
53  
54 that allows distinguishing and identifying the letters falling under the attentional focus  
55  
56  
57  
58  
59  
60

1  
2  
3 reflects visual magnocells problems in dyslexia (Vidyasagar, 2013; Vidyasagar & Pammer,  
4  
5 2010).

6  
7 It is noteworthy that both of the aforementioned theories assume that temporal  
8  
9 processing deficits at these different speeds in dyslexia would affect amodal processing  
10  
11 regardless of the verbal nature of the stimuli, and might both (primarily or secondarily) be  
12  
13 caused by a magnocellular deficit. However, the processing speed of non-verbal (e.g., tones  
14  
15 and dots) and verbal (phonemes and letters) sequences should differ since additional semantic  
16  
17 and syntactic computations will be involved in processing the latter but not the former  
18  
19 computations. Therefore, the specific rate at which a deficit will be visible should also  
20  
21 depend on the type of task performed. For this reason, we propose that the arbitrary and  
22  
23 relative terms “slow” and “fast” used to refer to the temporal deficits observed in dyslexia,  
24  
25 might be better redefined as processes that occur *between* or *within* task-relevant units,  
26  
27 respectively.  
28  
29  
30

31  
32 In this paper, we will argue that slow temporal processing *between* units corresponds  
33  
34 to an oscillatory “parsing” mechanism which would set auditory temporal and visual  
35  
36 spatiotemporal boundaries onto when and where to focus attention on the signal, and help  
37  
38 encode the order of information in the sequence. Fast temporal processing *within* these parsed  
39  
40 units would correspond to a high resolution oscillatory “sampling” yielding their  
41  
42 identification. We will then propose that an atypical development of these temporal  
43  
44 mechanisms might lead to dyslexia, and that the strength of these deficits will be modulated  
45  
46 by the intrinsic spatiotemporal statistical structures conveyed by the language(s) learned.  
47  
48  
49  
50

## 51 52 **2. The contribution of auditory and visual neural oscillatory activity to reading**

53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 We can distinguish between languages because cognitive and neural mechanisms are  
4 sensitive enough to subtle phonological and orthographic timing variations. In fact, our brain  
5 is fundamentally rhythmic and is programmed to pick up fine grain temporal modulations.  
6 Oscillatory activity in the brain (i.e., the alternation between excitatory and inhibitory  
7 moments where populations of neurons will or won't fire) synchronizes to the regularities  
8 present in one's environment, which in turn generates the phenomenon of neural entrainment  
9 (Calderone, Lakatos, Butler & Castellanos, 2014). In our view, the entrainment of brain  
10 signals would be a possible neural underpinning for parsing (attentional shifting), that, in  
11 turn, would affect sampling (attentional focusing) mechanisms. We hypothesize that if the  
12 quality of oscillatory neural processes across sensory modalities contributes to building-up  
13 optimal predictions of *what* (information sampling) happens *when* (parsing strategies) in  
14 linguistic sequences, these neurophysiological responses should explain the manifestations of  
15 the temporal processing deficits described in dyslexia. We want to make it clear here that, in  
16 the same line of reasoning as other authors (Seidenberg, 2001; Sprenger-Charolles & Colé,  
17 2013), we are not seeking to explain the heterogeneity of the manifestations of dyslexia with  
18 a sole, unitary mechanism. For example, we will argue that different oscillatory frequency  
19 bands for visual and auditory temporal processing support distinct neural mechanisms that  
20 might (i) contribute differentially to phonological and reading acquisition, (ii) be modulated  
21 by cross-linguistic differences, and (iii) lead to possible various dyslexic cognitive and  
22 reading subtypes. Overall, this article is an attempt to re-interpret (and integrate) previous  
23 theories of dyslexia in light of recent findings about oscillatory neuronal activity, and aims at  
24 assisting clinicians in their diagnosis of dyslexia.  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50

## 51 52 53 54 **2.1 Auditory oscillations and developmental dyslexia** 55 56 57 58 59 60

1  
2  
3 Some appealing theories of dyslexia (see Giraud & Ramus, 2013; Goswami, 2011) attribute a  
4 causal role to auditory atypical oscillatory neural activity, suggesting it generates some of the  
5 phonological problems in dyslexia. These theories propose that auditory cortical oscillations  
6 of dyslexic individuals entrain less accurately to the spectral properties of auditory stimuli at  
7 distinct frequency bands, and that these deficits are accompanied by specific hemispheric  
8 lateralization patterns. For example, Goswami (2011) argues that dyslexia stems from  
9 atypical right hemisphere-dominant neural entrainment to slow-rate prosodic (delta band,  
10 0.5–1 Hz) and syllabic (theta band, 4–8 Hz) speech modulations, which are defined by salient  
11 rise-time in amplitude (i.e., the envelope) generating speech rhythm (see Figure 1).  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22

23 ---FIGURE 1---  
24  
25  
26

27 Accordingly, Hämäläinen, Rupp, Soltész, Szücs, and Goswami (2012) found right  
28 hemisphere atypical phase-locking to slow (delta) auditory nonverbal modulations in dyslexic  
29 adults. In the same vein, Abrams, Nicol, Zecker, and Kraus (2009) reported a deficit in delta  
30 oscillatory neural response to natural speech stimuli. Recently, Molinaro, Lizarazu, Lallier,  
31 Bourguignon, and Carreiras (2016) showed that compared to skilled readers, both dyslexic  
32 adults and children exhibited low brain synchronization to speech in the delta band in the  
33 right hemisphere (see also Power, Colling, Mead, Barnes, & Goswami, 2016) that  
34 furthermore impeded subsequent neural oscillatory processes in the left hemisphere.  
35 Molinaro et al. (2016)'s results are in line with the proposal of Giraud and Ramus (2013) that  
36 dyslexia could result from an impaired generation not only of slow neural oscillations in the  
37 right hemisphere, but also of left hemisphere-*biased*<sup>2</sup> high frequency neural oscillations that  
38 are related to phonemic sampling (>30 Hz, gamma band). The existence of both types of  
39 deficits in dyslexia could find an explanation in the hierarchical cross-frequency coupling  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55

56 <sup>2</sup> Fast neural entrainment might indeed be subtended by a bilateral network that we therefore consider *biased*  
57 towards the left hemisphere when compared to slower oscillatory functions whose brain substrates would be  
58 located in the right hemisphere (Scott & McGettigan, 2013).  
59  
60



1  
2  
3 mechanism that exists between the phase of low-frequency delta and theta bands oscillations  
4 and the amplitude (or power) of gamma activity in the auditory brain regions at play during  
5 typical speech perception (Gross et al., 2013; and see Figure 1. B.). There is some evidence  
6 that left hemisphere gamma activity in response to amplitude-modulated white noises is  
7 abnormal in adults with dyslexia (Lehongre, Ramus, Villiermet, Schwartz, & Giraud, 2011;  
8 Lizarazu et al., 2015). Similar anomaly in response to speech stimuli was also shown in  
9 absence of similar problems at slower frequency bands (Lehongre, Morillon, Giraud, &  
10 Ramus, 2013), supporting phonemic processing difficulties as the main phonological  
11 symptom associated with reading disorders. Despite these inconsistencies regarding the  
12 nature of the atypical oscillatory neural activity in dyslexia, i.e., some at low and others at  
13 high frequency bands (note that none of these studies looked at cross-frequency coupling),  
14 this suggests that the neural mechanisms supporting these two main oscillatory frequency  
15 ranges for auditory processing may play a role in reading acquisition.  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31

32 We propose that such data fit with the existence of the parsing and sampling mechanisms  
33 described above: the brain synchronization to low frequencies would generate consistent  
34 attentional shifts *between* salient prosodic units, and neural oscillatory activity at high  
35 frequencies would reflect the sampling of the phonemic content falling *within* the focus of  
36 attention. Moreover, we assume that the coupling between these two mechanisms would be  
37 critical: the phase of prosodic and syllabic speech parsing would guide where to focus  
38 attention for subsequent phonemic sampling. If this hypothesis and the amodality assumption  
39 of sensory temporal theories of dyslexia are correct, a similar atypical oscillatory neural  
40 mechanism in the visual modality should also contribute to dyslexia (Goswami, Power,  
41 Lallier, & Facoetti, 2014).  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55

## 56 **2.2. Visual oscillations and developmental dyslexia**

57  
58  
59  
60

1  
2  
3 Some evidence shows that visual orienting and focusing might indeed be mediated by  
4  
5 delta/theta (2–5 Hz) phase – gamma (>70 Hz) amplitude coupling arising in a “wide”  
6  
7 network including occipital, frontal and parietal areas (Szczepanski et al., 2014). Regarding  
8  
9 dyslexia, Vidyasagar (2013) proposed a visual oscillatory framework that relies on the fact  
10  
11 that reading engages similar resources as those required for visual search, through the  
12  
13 spatiotemporal sampling of letter strings. His idea is that the core visual oscillatory deficit in  
14  
15 dyslexia resides in spike-based low gamma activity (around 25–40 Hz) reflecting the serial  
16  
17 sampling of individual letters falling under the attentional focus. Whereas Vidyasagar (2013)  
18  
19 does not assign a critical role of lower frequencies to explain reading deficits, we suggest that  
20  
21 lower frequencies do contribute to the manifestations of dyslexia. Ito, Maldonado, and Grün  
22  
23 (2013) investigated visual neural oscillations during free visual scene exploration (a situation  
24  
25 that resembles reading), and showed the importance of both low and high frequency  
26  
27 oscillations including (i) the phase-locking of oscillatory activity to fixation onset in the  
28  
29 delta-theta frequency range (2–4 Hz, i.e., phase locking to the frequency of saccades), and (ii)  
30  
31 the modulation of low gamma power (20–40 Hz) tied to these eye movements. More  
32  
33 particularly, the stronger the phase-locking in the delta-theta ranges in the primary visual  
34  
35 cortex, the higher the increase in power of low-gamma activity in the same region. Therefore,  
36  
37 slow neural fluctuations phase-locked to voluntary eye movements (and overt attentional  
38  
39 shifting) influence fast oscillatory induced activity in the primary visual cortex (see also  
40  
41 Bosman, Womelsdorf, Desimone, & Fries, 2009). Moreover, Hoffman et al. (2014)  
42  
43 completed this picture showing that, during visual search, fixation onset triggers neural  
44  
45 phase-locking to theta oscillations in the hippocampus (3–8 Hz range) that lasts  
46  
47 approximately the time of the fixation (2 or 3 cycles).  
48  
49  
50  
51  
52  
53

54 Based on this evidence, we hypothesize that distinct slow visual oscillatory parsing  
55  
56 mechanisms may be at play during reading. This would include eye saccades (delta range)  
57  
58  
59  
60

1  
2  
3 that would guide where to move the eye on orthographic inputs. Then, we predict that the  
4  
5 resulting fixation would trigger a theta oscillatory rhythm aimed to parse in finer grains the  
6  
7 information that has fallen under fixation. We suspect that such theta rhythm may fall around  
8  
9 7 Hz, shown to reflect covert and automatic visual attentional shifting (Busch & VanRullen,  
10  
11 2010). Assuming that 7 to 9 letters on average are processed per fixation in about 200–250  
12  
13 ms (Rayner, 1998), this 7Hz attentional rhythm would parse 3- to 5-letter chunks per cycle,  
14  
15 possibly corresponding to the delimitation of syllables within the fixated letters. Moreover, it  
16  
17 is possible that theta oscillations play a particularly important role in encoding the order of  
18  
19 the parsed information within the attended speech and orthographic sequences (Roux &  
20  
21 Uhlhaas, 2014). We assume that both these low frequency mechanisms would define periods  
22  
23 of increased low gamma activity—resulting from cross-frequency coupling (Ito et al.,  
24  
25 2013)— reflecting the sampling of individual letters leading to their identification  
26  
27 (Vidyasagar, 2013).  
28  
29  
30  
31  
32  
33

### 34 **2.3. Possible neural origin(s) of amodal oscillatory deficits in dyslexia**

35  
36 Although determining the etiology of visual and auditory oscillatory deficits is not the  
37  
38 purpose of the present framework, we suspect that they might potentially result from  
39  
40 dysfunctions of a large network including sensory, attentional and language processing areas,  
41  
42 whose integrity may partly rely on subcortical areas such as the cerebellum and the thalamus.  
43  
44 Interestingly, the magnocellular system feeds heavily from the cerebellum (Stein & Walsh,  
45  
46 1997), and the thalamus plays a relay role between the cerebellum and cortical areas.  
47  
48 Moreover, both cerebellar and thalamic structures present a high number of connections with  
49  
50 networks involved in cognitive skills important for reading and dyslexia such as language and  
51  
52 visual attention (e.g., Cerebellum: Stoodley & Stein, 2011; Stoodley & Stein, 2013 for  
53  
54 reviews; Thalamus: Bundesen, Habekost, & Kyllingsbæk, 2005; Radanovic, Azambuja,  
55  
56  
57  
58  
59  
60

1  
2  
3 Mansur, Porto, & Scaff, 2003). Most importantly, both the cerebellum and the thalamus are  
4  
5 involved in coding the timing and tempo of events across modalities (Cerebellum: e.g., Hari  
6  
7 & Parkkonen, 2015; Kotz & Schmidt-Kassow, 2015; Kotz & Schwartz, 2010; Schwartz,  
8  
9 Keller, & Kotz, 2016; Thalamus: e.g., Panzeri, Brunel, Logothetis, & Kayser, 2010; Teki,  
10  
11 Grube, Kumar, & Griffiths, 2011) and may play an important role in the development of  
12  
13 predictive top-down perceptual coding networks (Kashino & Kondo, 2012; Roth, Synofzik,  
14  
15 & Lindner, 2013) that could be subtended by oscillatory entrainment in low frequency bands  
16  
17 (Park, Ince, Schyns, Thut, & Gross, 2015). Therefore, it is possible that oscillatory  
18  
19 dysfunctions in dyslexia either originate in the cerebellum and/or the thalamus, or stem from  
20  
21 of a deficient cortical mechanism that would prevent the tuning of specific cerebellar and/or  
22  
23 thalamic nuclei for oscillatory development.  
24  
25

26  
27 Accordingly, some of the structural or functional properties of these sub-cortical areas  
28  
29 have been shown to be linked to normal reading and developmental dyslexia (Cerebellum:  
30  
31 Jednoróg et al., 2015; Pernet, Poline, Demonet, & Rousset, 2009; Stoodley, 2015;  
32  
33 Thalamus: Díaz, Hintz, Kiebel, & von Kriegstein, 2012; Galaburda, Menard & Rosen 1994;  
34  
35 Jednoróg et al., 2015; Livingstone, Rosen, Drislane, & Galaburda 1991; Pugh et al., 2013;  
36  
37 Szalkowski, Booker, Truong, Threlkeld, Rosen, & Fitch, 2013). Moreover, several studies  
38  
39 reported “cerebellar symptoms” in the dyslexic population (e.g., Fawcett, Nicolson & Dean,  
40  
41 1996; Nicolson, Fawcett, & Dean, 2001; Stoodley, Harrison, & Stein, 2006; Stoodley,  
42  
43 Fawcett, Nicolson, & Stein, 2005).  
44  
45

46  
47 Future studies should strive to investigate the potential links between speech and  
48  
49 visual attentional neural oscillatory networks and cerebellar and thalamic dysfunctions in  
50  
51 normal reading acquisition and dyslexia.  
52  
53  
54  
55

#### 56 **2.4 Is the amodal oscillatory deficit in dyslexia really amodal?**

57  
58  
59  
60

1  
2  
3 The amodal hypotheses of dyslexia suggest that deficits should be found in both the visual  
4 and auditory modalities using as analogous paradigms as possible in the same individual.  
5  
6  
7 Some studies support this hypothesis (e.g., Facoetti, Lorusso, Cattaneo, Galli & Molteni,  
8 2005; Lallier et al., 2009; Meyler & Breznitz, 2005) and highlight amodal deficits at the  
9  
10 individual level through case studies or correlation analyses across modalities (Lallier,  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
Reed, 1989). Therefore, we propose that amodal deficits should refer to the existence of  
auditory and visual deficits in the dyslexic population *as a whole* but not systematically  
*within one individual* (see Ramus et al., 2003).

For our framework, this implies that a specific deficit in one frequency band in the auditory  
modality may not *always* co-occur with similar deficit in the visual modality in the same  
individual (and vice versa). Several hypotheses (not mutually exclusive) can explain why,  
including the following. Firstly, amodal oscillatory-based manifestations of dyslexia may  
stem from independent dysfunctions of distinct reading circuits, i.e., restricted to either visual  
areas, auditory areas, or expanding to both. Secondly, oscillatory functions may be more  
relevant for reading acquisition in one modality compared to the other depending on the  
developmental stage of language and reading skills. More specifically, auditory deficits  
should be visible at earlier stages than visual difficulties (see Figure 2). Lastly, the  
phonological and orthographic properties of the language learned should modulate the  
auditory and visual deficits observed. We will fully discuss this last hypothesis in the  
remainder of this article where we propose that cross-linguistic oscillatory research in

dyslexia can shed light on inconsistencies in the field and help clinical practice with the interpretation of various dyslexic symptoms.

---FIGURE 2---

### 3. Cross-linguistic influence on neural oscillations in dyslexia

The evidence presented above suggests that across sensory modalities, slow and fast oscillatory mechanisms as well as their hierarchical coupling may play a role in reading acquisition and dyslexia.

We hypothesize that extensive experience with one (or more) language(s) will affect the contribution of neural oscillatory mechanisms to reading development, depending on linguistically-evoked phonological and orthographic spatiotemporal rhythms. Therefore, if cross-linguistic variations have an impact on the developmental time course of neural oscillatory activity, oscillatory neural dysfunctions and reading deficits associated with dyslexia should manifest themselves differently across languages (see section 4.).

Importantly, we assume that language-specific spatiotemporal rhythms will not affect the development of both parsing and sampling oscillations to the same degree. In the auditory modality, parsing mechanisms in the delta and theta ranges are respectively driven by prosodic and syllabic modulations of the amplitude of the auditory signal (Giraud & Poeppel, 2012). In the visual modality, we proposed earlier that the chunking of letter strings would be determined by visuo-motor and visuo-attentional events occurring in the delta and theta ranges, respectively corresponding to saccades (overt attentional shifting) and covert attentional shifts.

On the one hand, since these slow oscillatory mechanisms are externally evoked by and phase-locked to the properties of speech and orthographic inputs, such as linguistic rhythm and orthographic depth, parsing mechanisms may be particularly sensitive to cross-linguistic variations. On the other hand, sampling strategies reflected in gamma oscillations across

1  
2  
3 sensory modalities might be mainly indirectly affected by cross-linguistic structural  
4 variations (see section 3.2.): through phase-amplitude coupling mechanisms, language-  
5 specific parsing strategies will determine the variations observed on the contribution of  
6 sampling mechanisms to reading acquisition.  
7  
8  
9  
10

### 11 12 13 14 **3.1. Cross-linguistic impact on slow oscillatory parsing mechanisms (delta and theta** 15 **bands).** 16 17

18  
19  
20 Firstly, we will present evidence of the influence of cross-linguistic variations on  
21 oscillatory mechanisms involved in oral (auditory) language development taking place before  
22 written (visual) language acquisition. Accurate speech analysis from birth contributes to  
23 developing and training phonological sensitivity (e.g., phonological short term memory,  
24 phonological awareness) that will be required for the acquisition of reading years later.  
25 Indeed, dyslexia may (partly) be the consequence of impaired attentional and auditory  
26 speech-related processes already at play from the very first stages of life (e.g., Guttorm,  
27 Leppänen, Richardson, & Lyytinen, 2001; Guttorm et al., 2005).  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37

38  
39 Secondly, we will focus on the impact of cross-linguistic variations regarding oscillatory  
40 parsing mechanisms that result from the exposure to written language. We will show that  
41 orthographic-specific differences in the regularity and predictability of grapheme-to-phoneme  
42 conversions (i.e., orthographic depth and the grain size, Ziegler & Goswami, 2005) should  
43 have an important role to play in visual oscillatory parsing mechanisms and the  
44 manifestations of dyslexia across languages.  
45  
46  
47  
48  
49  
50  
51

#### 52 53 54 **3.1.1. Auditory modality: the role of linguistic rhythm in cross-linguistic variations.** 55 56 57 58 59 60

1  
2  
3 Brain oscillations entrain to the rhythmicity of speech-relevant amplitude modulations  
4 (prosody/delta; syllables/theta; Giraud & Poeppel, 2012), and such entrainment is thought to  
5 enhance speech perception and language acquisition (Kotz & Schwartz, 2010; Winkler,  
6 Denham, & Nelken, 2009). Auditory attention—which contributes to the development of  
7 phonological skills important for reading development—might therefore act as an attentional  
8 oscillator whose sequential shifts are tuned and attracted by linguistic rhythms (Quené &  
9 Port, 2005), which significantly vary between languages (e.g., Ramus, Nespors, & Mehler,  
10 1999).

11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21 There is evidence suggesting that the encoding of stressed units in speech (i.e., what  
22 generates speech rhythm) is a fundamental mechanism that contributes to language and word  
23 learning (e.g., Curtin, 2010). Stressed speech units help infants segment and encode speech  
24 by automatically orienting the auditory attentional focus towards important information in a  
25 continuous stream of speech segments. When lacking semantic lexical knowledge, infants  
26 may take advantage of the distributional properties of stressed units in the continuous stream  
27 of phonemes, whose order may seem random at these early developmental stages.

28  
29  
30  
31  
32  
33  
34  
35  
36 Therefore, low frequency speech modulations will be used as an oscillatory phonological  
37 framework to parse and acquire new vocabulary (Leong, Kalashnikova, Burnham, &  
38 Goswami, 2014), which will itself significantly contribute to reading acquisition (Ziegler,  
39 Perry & Zorzi, 2014). How does this rhythmic framework vary across languages? Although  
40 stress is a universal speech prosodic feature, linguistic-specific differences affect the degree  
41 of its position predictability in words (Peperkamp, Vendelin, & Dupoux, 2010). Indeed, not  
42 all languages present the same sets of rules that govern how (i.e., where and when) lexical  
43 stress is assigned over words. Some languages carry unpredictable lexical stress (e.g.,  
44 English, Spanish) whereas others don't (e.g., French, Basque). In English, Spanish and  
45 Italian, the lexical stress pattern changes depending on the word itself, and moreover, stress  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60



1  
2  
3 can be used to differentiate between words with the exact same sequence of phonemes (e.g.,  
4 in Spanish, /'bebe/, “s/he drinks” vs /be'be/, “baby”) and also orthographically identical (In  
5 Italian, /'ancora/, “anchor” vs /an'cora/, “still/again”). In French, lexical stress is not  
6 contrastive and is so predictable that learners become insensitive to it, to the point of ‘stress  
7 deafness’ (Dupoux, Pallier, Sebastian, & Mehler, 1997). This is because when a French word  
8 carries stress, it always falls on the last syllable. Learners of languages with highly  
9 predictable lexical stress position are still able to process the acoustic correlates of stress  
10 (Christophe, Peperkamp, Pallier, Block, & Mehler, 2004), but show a specific perceptual  
11 ‘insensitivity’ to lexical stress encoding, which would result in its under-representation (or no  
12 representation at all) in the lexical phonological memory of these linguistic groups (Dupoux,  
13 Peperkamp, & Sebastián-Gallés, 2010).

14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28 Further evidence for the claim that speakers of languages with predictable stress are ‘stress  
29 deaf’ is apparent in an experiment in which Basque monolingual infants were shown to be  
30 less sensitive than their Spanish peers to perceive changes affecting the acoustic correlates of  
31 stress (Molnar, Lallier & Carreiras, 2014): nine-month-old Basque infants did not show any  
32 sensitivity to language-specific patterns of tone duration compared to their Spanish peers.  
33 Importantly, the lack of sensitivity to lexical stress in speakers of languages with predictable  
34 lexical stress persists in adulthood, even if a language with unpredictable lexical stress  
35 patterns is learned early in the teenage years (Dupoux, Sebastián-Gallés, Navarrete, &  
36 Peperkamp, 2008). Cross-linguistic differences on the perception of lexical stress is therefore  
37 stable across time, suggesting that native language’s lexical stress predictability strongly  
38 tunes speech analysis and the importance of prosody for encoding spoken words in memory.  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50

51  
52 We propose that a low predictability of lexical stress position in a language enhances the  
53 importance and relevance of stress encoding linked to the word (lexical stress), and increases  
54 the sensitivity to perceptual mechanisms responsible for such encoding. Therefore, it is  
55  
56  
57  
58  
59  
60

1  
2  
3 reasonable to assume that learners of such languages (e.g., English and Spanish) may tune  
4  
5 more strongly their neural oscillations toward slow speech modulations, in the delta and theta  
6  
7 bands in particular. Goswami and Leong (2013) propose that in order to encode the position  
8  
9 of stress within words, listeners have to learn with great precision how to align the phase of  
10  
11 neural oscillations corresponding to both the stress (delta) and syllable (theta) speech  
12  
13 modulation rates. These authors also propose that this phase alignment mechanism may be  
14  
15 affected in dyslexia, and contribute to the associated auditory perceptual deficits and  
16  
17 phonological disorders (see Figure 3).  
18  
19

20  
21 ---FIGURE 3---  
22

23 We suggest that neural entrainment at low frequency bands subtended by the right  
24  
25 hemisphere should play a crucial role in reading acquisition for these languages where lexical  
26  
27 stress is not predictable. In languages where lexical stress is highly predictable, this phase  
28  
29 alignment would not be so important, at least to build lexical phonological traces in memory  
30  
31 (see Figure 3). Thus, we expect atypical right hemisphere neural oscillatory sampling at low  
32  
33 frequency bands to be less severe in dyslexic individuals in languages like French when  
34  
35 compared to their skilled reader peers, who would themselves exhibit ‘lower’ functioning of  
36  
37 this network (i.e., the ‘stress deafness’ phenomenon) than skilled readers of languages with  
38  
39 unpredictable lexical stress like English. However, we hypothesize that French dyslexic  
40  
41 participants are likely to suffer from a *shallow* lexical stress processing deficit that would  
42  
43 come to light when the resources devoted to lexical stress encoding are pushed to their limits  
44  
45 in difficult situations (Soroli, Szenkovits, & Ramus, 2010); hence, this deficit would be less  
46  
47 (or not) apparent in passive easy naturalistic conditions (Lehongre et al., 2013). Conversely,  
48  
49 lexical stress-related neural oscillatory activity would be boosted in English speakers because  
50  
51 of its importance for English word acquisition, and larger gaps would emerge between skilled  
52  
53 and dyslexic readers on this aspect, exacerbating the deficits. If this hypothesis is correct,  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 future studies should report that atypical neural entrainment to low frequencies in dyslexia  
4  
5 (Abrams et al. 2009; Hämäläinen et al., 2012) specifically affects stress processing tied to  
6  
7 lexical rather than phrasal speech units<sup>3</sup>. Indeed, phrasal prosody carries syntactic and  
8  
9 grammatical phonological information (Nespor, Shukla, van de Vijver, Avesani, Schraudolf,  
10  
11 & Donati, 2008; Gervain & Werker, 2013) whose processing is typically preserved in  
12  
13 dyslexia, but impaired in populations with specific language impairments (Bishop &  
14  
15 Snowling, 2004).  
16  
17

18  
19 In addition to the predictability of lexical stress position, it should be useful for future  
20  
21 studies to also look at parameters that have been shown to contribute to the generation of  
22  
23 linguistic rhythm. Researchers have put forward some classifications of languages based on  
24  
25 their rhythm class (syllable-timed *versus* stress-timed; e.g., Ramus, et al., 1999). One of these  
26  
27 parameters (namely the variability of vocalic interval duration, speech rate-normalised) was  
28  
29 later found to be the strongest predictor of the degree of ‘nativeness’ of an accent (White &  
30  
31 Mattys, 2007). White and Mattys’ (2007) results suggest that this parameter is important for  
32  
33 native speech prosodic analysis. According to their classification, a syllable-timed language  
34  
35 like Spanish was found to be associated with more regular, hence less variable, vocalic  
36  
37 interval duration, than languages such as French or English. Since temporal rhythmic  
38  
39 regularities in a language help listeners predict when (or where) salient information occurs in  
40  
41 speech (Kotz & Schwartze, 2010), we expect neural oscillatory entrainment to be stronger at  
42  
43 this rate (theta, 4–7 Hz) in Spanish than in French or English. The low variability that  
44  
45 characterizes vocalic intervals in Spanish could somehow offer a way to cope with atypical  
46  
47 neural entrainment at low frequency bands in dyslexia, and to get around potential difficulties  
48  
49 for encoding the position of lexical stress. Accordingly, Lizarazu et al. (2016) found that  
50  
51  
52  
53

---

54  
55 <sup>3</sup> It is noteworthy that the processing of phrases that correspond to multiword expressions (e.g., book titles, TV  
56 shows names) may engage similar computations as those used for processing lexical units (Molinaro, Canal,  
57 Vespignani, Pesciarelli, & Cacciari, 2013; Molinaro, Vespignani, Canal, Fonda & Cacciari, 2008), and could  
58 therefore be impaired in developmental dyslexia (for example, see deficits in the “DeeDee task” of Goswami,  
59 Gerson & Astruc, 2010).  
60

1  
2  
3 Spanish dyslexic readers had increased auditory entrainment to the theta band compared to  
4  
5 their skilled reader peers. This might offer a compensatory mechanism which dyslexic  
6  
7 individuals could rely on to improve their ability to align the phase of theta (syllable) and  
8  
9 delta (stress) oscillatory rates. However, it may also exacerbate deficits if a dysfunction of the  
10  
11 neural entrainment at this band (theta) prevents dyslexic individuals from exploiting these  
12  
13 metric regularities<sup>4</sup>.  
14  
15  
16  
17

### 18 **3.1.2. Visual modality: the role of orthographic depth in cross-linguistic variations**

19

20  
21  
22  
23 One of the most studied modulators of reading acquisition across languages is  
24  
25 orthographic depth. Alphabetic writing systems differ in the complexity, consistency, and  
26  
27 predictability with which the graphemes map onto their corresponding phonemes (Schmalz,  
28  
29 Marinus, Coltheart & Castles, 2015). In 2005, Ziegler and Goswami proposed the  
30  
31 psychological grain size theory to explain orthography-specific variations observed on  
32  
33 reading development and dyslexia. The grain size refers to the length of the graphemes, the  
34  
35 orthographic units that are relevant for phonemic access and manipulation. Ziegler and  
36  
37 Goswami (2005) concluded that the deeper the orthography, the larger the size of the units  
38  
39 used for lexical learning in a given language. Shallow orthographies like Spanish favour the  
40  
41 use of one-letter units since they consistently correspond to individual phonemes.  
42  
43 Conversely, in deep orthographies, like English, a whole group of letters can refer to one  
44  
45 sound and the same letter will sometimes map into different sounds depending on its adjacent  
46  
47 context in the word (e.g., *pint versus mint*). Therefore, the regularity and consistency of  
48  
49 grapheme-to-phoneme conversions of shallow orthographies results in the use of smaller  
50  
51  
52  
53

---

54  
55  
56 <sup>4</sup> Vocalic interval duration variability may contribute to building up predictions of when the onset of syllabic  
57  
58 units occurs in speech. The perceptual sensitivity to syllabic onsets should be linked to the sensitivity to  
59  
60 perceptual centers (onset of vowels) and rise-times (onset of syllables), which are two acoustic parameters that  
may explain atypical auditory neural sampling at low frequency bands in dyslexia (cf Goswami & Leong, 2013).

1  
2  
3 grains for reading than what is observed in deep orthographies (e.g., Ellis & Hooper, 2001;  
4  
5 Seymour, Aro & Erskine, 2003).  
6

7         Rau, Moll, Snowling, and Landerl (2014) used eye tracking measures to examine  
8 cross-linguistic variations on graphemic parsing strategies between English (deep) and  
9 German (shallow) children when reading in their native language. They showed that English  
10 readers needed to parse larger orthographic sequences than German readers. Similar cross-  
11 linguistic variations were reported in bilingual individuals. Lallier, Acha, and Carreiras  
12 (2016) showed that learning to read in a deep orthography such as French in addition to a  
13 shallow one, i.e., Basque, enhanced the size of the visual chunks attended to in reading and  
14 reading-related tasks performed in Basque compared with learning to read in two shallow  
15 orthographies, i.e., Spanish and Basque (see also Lallier, Carreiras, Tainturier, Savill, &  
16 Thierry, 2013). These studies highlight the existence of cross-linguistic transfer and  
17 interactions in bilinguals that have an impact on the orthographic parsing strategies used by  
18 these individuals (see Lallier & Carreiras, under review, for a review).  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33

34         Here, we make a step forward in proposing that cross-linguistic variations on the grain  
35 size will lead to differences in slow oscillatory visual rhythms induced by experience with the  
36 depth of the orthography. In fact, even though orthographic sequences are not temporal  
37 stimuli and do not trigger a rhythmic pattern *per se*, it is likely that neural oscillations  
38 modulate the perceptual sensitivity for their identification (Busch & Van Rullen, 2014).  
39  
40  
41  
42  
43  
44

45         In particular, slow visual oscillatory neural rhythms will guide when and where to move  
46 the eye over orthographic sequences to define the length of the units to be parsed (i.e.,  
47 number of visual elements falling under fixation). Our rationale is that the importance of  
48 delta rhythms (eye saccade frequency, overt attentional shifts) and its coupling with theta  
49 rhythms (covert attentional shifting under fixation) may vary between languages (see Figure  
50 4). Whereas only one eye fixation will generally occurs over words during expert reading  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 (lexical processing), several fixations within words may be necessary for phonological  
4 decoding at the beginning of reading acquisition, similarly as what is observed during  
5 pseudoword reading (Hutzler & Wimmer, 2004). In deep orthographies, we suggest that  
6 multi-letter graphemes will have to be parsed and fixated as a whole to learn the correct  
7 phonological corresponding mappings. Moreover, flexible and accurate delta-theta coupling  
8 should be necessary in deep orthographies since the size of the multi-letter units to be parsed  
9 varies between words (e.g., *tlough* versus *plllough*, in English). In shallow orthographies, this  
10 process may matter less for reading acquisition, in that visual boundaries (such as those  
11 determined by multi-letter graphemes) do not constrain as much the accuracy of grapheme-  
12 to-phoneme conversions, and that the size of the parsed units would not vary so much  
13 between words (see Figure 4). Therefore, a poor monitoring of slow visual oscillatory  
14 mechanisms (i.e., coupling between delta and theta oscillations, and interactions between eye  
15 movements and covert attentional shifting) may be more detrimental for reading acquisition  
16 in deep compare to shallow orthographies.  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32

33  
34 ---FIGURE 4---  
35

36 **I**n addition, the need to use various grain size to cope with complex grapheme-to-phoneme  
37 mappings in deep orthographies may also slow down the speed of covert attentional shifting  
38 skills over words (theta rhythm around 7 Hz; see section 2.2.), which may partly explain why  
39 reading acquisition rate is slower in deep compared to shallow orthographies (Seymour et al.,  
40 2003). Indeed, at the beginning of reading acquisition, the main use of small orthographic  
41 grains through phonological decoding should benefit from temporally consistent automatic  
42 attentional shifting between units. Since shallow orthographies boost the use of small grains  
43 and of phonological decoding (Richlan, 2014), visual sluggish attentional shifting may be  
44 more visible (and more detrimental) in these orthographies. We expect sluggish attentional  
45 shifting to be indexed by an inconsistent phase of theta visual oscillations. Therefore,  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 inconsistent phase of theta visual oscillations may be more detrimental in shallow compared  
4  
5 to deep orthographies for which shifting abilities may be already sluggish because of the need  
6  
7 to use various grain sizes in order to cope with complex grapheme-to-phoneme mappings.  
8

9  
10 It is important to note that other factors than orthographic depth might modulate the  
11  
12 use of some optimal grain size and slow visual oscillatory rhythms compared to others. As  
13  
14 suggested above, small grain strategies are extremely important for acquiring reading at early  
15  
16 developmental stages, whereas large grain ones might be equally important across  
17  
18 development (Bosse & Valdois, 2009; Ziegler et al., 2014). Moreover, other items'  
19  
20 characteristics may impose some constraints on slow visual parsing mechanisms: unfamiliar  
21  
22 and infrequent words are likely to engage decoding and small grain strategies, while familiar  
23  
24 and frequent word reading is prone to rely on lexical and large grain strategies. Therefore, we  
25  
26 expect cross-linguistic differences based on orthographic depth to be also modulated by the  
27  
28 processing demands of the reading situation itself. Table 1 summarizes hypotheses regarding  
29  
30 the reading strategies and oscillatory visual mechanisms that might be more heavily recruited  
31  
32 in deep and shallow orthographies, as well as the reading situations that may be facilitated by  
33  
34 the use of specific grain sizes.  
35  
36  
37

38 ---TABLE 1---

### 39 40 **3.2. Cross-linguistic impact on fast oscillatory sampling mechanisms in the gamma** 41 42 **band.** 43 44

#### 45 46 47 **3.2.1. Auditory gamma oscillations** 48 49

50  
51 It is important to determine what is going to be the cross-linguistic impact on the  
52  
53 development of fast auditory sampling mechanisms related to phonemic speech processing  
54  
55 (Giraud & Poeppel, 2012), because it is a significant pre-requisite of reading acquisition, at  
56  
57  
58  
59  
60

1  
2  
3 least in alphabetic languages (e.g., Frith, 1986; Snowling, 1981). Firstly, we will present how  
4  
5 the modulation of slow speech oscillations by linguistic rhythms may have an impact on the  
6  
7 manifestations of sampling deficits in dyslexia that are reflected in the gamma oscillatory  
8  
9 band. Secondly, we will show how linguistic-specific phonotactic and orthographic structures  
10  
11 may modulate atypical fast sampling mechanisms in dyslexia independently of the slow  
12  
13 auditory oscillatory prosodic properties of language.  
14  
15

16  
17 Earlier, we proposed that a higher contribution of slow auditory oscillatory parsing  
18  
19 mechanisms to phonological and reading development would characterize languages with  
20  
21 unpredictable lexical stress, such as English, compared to those with highly predictable  
22  
23 lexical stress, such as French. Therefore, we reason that in languages with predictable lexical  
24  
25 stress position, auditory attentional and perceptual resources may be (re-)directed to  
26  
27 processing phonemic information in speech at earlier developmental stages than in languages  
28  
29 with unpredictable lexical stress. For example, Skoruppa, Pons, Bosch, Christophe, Cabrol,  
30  
31 and Peperkamp (2013) showed that, compared to their Spanish peers, nine-month-old French  
32  
33 infants were unable to discriminate two pseudowords that differed in their stress pattern *and*  
34  
35 that were phonetically different (i.e., /'tuli/ vs /pi'ma/). French infants became able to  
36  
37 discriminate the items when they were phonetically similar (/pi'ma/ vs /'pima/). Therefore,  
38  
39 when infants' auditory attention was moved away from phonetic variability (i.e., when lexical  
40  
41 stress information is the only cue that allows them to differentiate the items), they started  
42  
43 noticing and processing the prosodic cues in their language (see also Dupoux et al., 1997).  
44  
45 We hypothesize that such differences would lead to exacerbated atypical fast gamma-related  
46  
47 sampling in dyslexic individuals in languages of predictable stress since slow oscillatory  
48  
49 networks would be less relevant for expert reading development (as shown in Lehongre et al.,  
50  
51 2013).  
52  
53  
54  
55  
56  
57  
58  
59  
60



1  
2  
3 We do not imply that dyslexic individuals of languages with unpredictable lexical stress  
4 should not exhibit any anomalies on left-hemisphere biased gamma activity. In fact, in these  
5 languages, the right hemisphere-dominant encoding of prosodic lexical information may have  
6 a particularly important role to play in fast oscillatory sampling mechanisms biased towards  
7 the left hemisphere, like phonemic categorization (Gandour, Wong, Hsieh, Weinzapfel, Van  
8 Lancker, & Hutchins, 2000). In these languages, cross-frequency coupling mechanisms  
9 (Gross et al., 2013) would result in atypical slow oscillations elicited by speech prosodic  
10 modulations to cause an impairment of sampling mechanisms at higher oscillatory  
11 frequencies (Goswami, 2011). For this reason, we assume that in English compared to  
12 French, cross-frequency coupling within the left and right auditory oscillatory networks (i)  
13 might have a greater contribution to reading and dyslexia, and (ii) might result in more visible  
14 dysfunctions in both the slow and fast oscillatory auditory neural networks supporting the  
15 acquisition of phonological knowledge. Moreover, according to hypotheses suggesting that  
16 an impaired access to this knowledge may be the core phonological deficit in dyslexia (Boets  
17 et al., 2013; Ramus & Szenkovitz, 2008; Ramus, 2014), we expect dyslexic individuals in  
18 languages with unpredictable stress like English to be impaired both on the encoding of the  
19 prosodic representations of words (like the ‘stress deaf’ French speakers, Dupoux et al.,  
20 2010) and on the access of phonological representations (Boets et al., 2013), whereas  
21 dyslexic individuals in languages with highly predictable lexical stress like French might  
22 exhibit shallow prosodic processing deficits but strong phonological access problems that we  
23 assume would rely on auditory processes related to gamma oscillatory activity.  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48

49 We will now briefly present evidence on how cross-linguistic differences could directly  
50 influence the development of fast auditory oscillatory sampling, independently of cross-  
51 frequency coupling mechanisms. Some language-specific characteristics may modulate the  
52 way cerebral gamma oscillations are tuned towards the sampling of speech amplitude  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 modulations reflecting phonemes. The saliency of segmental information may itself be  
4  
5 enhanced by some specific features of a language. For example, phonotactics has been shown  
6  
7 to influence the development of phonological awareness skills. More specifically, research  
8  
9 reports that the most frequent phonological syllabic structure in a language modulates the  
10  
11 phonological awareness abilities of children (e.g., Caravolas & Bruck, 1993; Caravolas &  
12  
13 Landerl, 2010). These skills are in fact tuned toward a language-specific grain size that could  
14  
15 encompass the phonemic, syllabic or morphemic levels depending on the rules of their  
16  
17 language (Goswami & Ziegler, 2006). Our proposal here is that the greater the sensitivity to  
18  
19 small phonological grains for speech segmental analysis, the higher the contribution of fast  
20  
21 auditory neural sampling and left hemisphere-biased networks to the development of  
22  
23 phonological awareness and reading. Assuming that gamma-related neural oscillations is  
24  
25 atypical in dyslexia, larger gaps would emerge between skilled and dyslexic readers in  
26  
27 languages whose phonological structure triggers the use of small phonological grains,  
28  
29 compared to languages whose phonological structure does not.  
30  
31  
32  
33

34  
35 Lastly, the manifestations of atypical fast auditory neural sampling in dyslexia can also be  
36  
37 influenced by orthographic depth variability between languages. We suggest that the degree  
38  
39 of consistency and transparency of graphemes-to-phonemes conversions should have a role to  
40  
41 play in the fine grain tuning of neural oscillations at high frequency bands in the auditory  
42  
43 modality. Because print exposure and phonemic awareness share reciprocal relationships, the  
44  
45 shallower the orthography, the faster children acquire reading and become aware of the  
46  
47 phonemic categories of their language (Landerl, et al., 2012; Seymour et al., 2003; Ziegler &  
48  
49 Goswami, 2005). Children learning to read in deep orthographies should allocate more left-  
50  
51 lateralized resources than children in shallow orthographies for accessing language sounds  
52  
53 from print (Brem et al., 2010), which would be indexed by increased gamma activity.  
54  
55 Therefore, we expect the formal exposure to the irregular and inconsistent letter-sound  
56  
57  
58  
59  
60

1  
2  
3 correspondences of a deep orthography to impose a cost on the already developed auditory  
4 phonological system. This cost should be particularly high if the left hemisphere-biased  
5 oscillatory system is already impaired as suggested by causal hypotheses linking atypical  
6 auditory neural sampling and dyslexia (Lehongre et al., 2011; Lehongre et al., 2013).  
7  
8  
9  
10

### 11 12 13 14 **3.2.2. Visual gamma oscillations** 15

16  
17  
18 We proposed earlier that orthographic depth may influence delta and theta oscillatory  
19 visual rhythms engaged in orthographic parsing. We will now argue that orthographic depth  
20 will have an impact on the width of the attentional focus (number of elements that can be  
21 processed simultaneously under fixation) and the underlying fast sampling reflected in  
22 gamma oscillatory activity.  
23  
24  
25  
26  
27  
28

29  
30 We suggest that the larger the chunks delimited by the phase and amplitude of theta  
31 oscillations, the higher the demand for their identification and the associated gamma activity:  
32 within the time window of fixation (inferior or equal to 250 ms in average, corresponding to  
33 theta rhythm) it will be less costly to sample two compared to five letters in one theta cycle.  
34 Therefore, visual sampling reflected in gamma oscillatory activity should be especially  
35 optimal when the orthographic grain size is large, like in deep orthographies.  
36  
37  
38  
39  
40  
41  
42

43 Interestingly, the number of distinct visual elements (e.g., letters) that can be processed  
44 simultaneously (defined as the time of one single eye fixation, hence within one theta cycle)  
45 has been shown to significantly contribute to reading and to be a potential proximal cause of  
46 reading deficits independently of phonological disorders (Bosse & Valdois, 2009; Lobier,  
47 Zoubrinetzky, & Valdois, 2012; Valdois et al., 2014). The notion of visual attention span has  
48 been proposed to refer to these resources in relation to reading and dyslexia and is classically  
49 assessed with whole and partial report tasks (Bosse et al., 2007). We propose that gamma  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 power may therefore be indicative of how much visual attentional resources are available for  
4  
5 the simultaneous processing of visual stimuli<sup>5</sup>. Therefore, if attentional resources reflected in  
6  
7 gamma power and made available to perform a task are too low to accurately identify large  
8  
9 grains such as irregular and inconsistent multi-letter chunks, only a subset of the parsed  
10  
11 letters will be processed. In that particular case, the system may switch to an attentional theta  
12  
13 oscillatory shifting mode (Frey et al., 2014; VanRullen, Carlson & Cavanagh, 2007) to  
14  
15 identify the letters not simultaneously but sequentially through more than one theta cycles  
16  
17 (see Lisman & Jensen, 2013). In the case of deep orthographies, we assume that this situation  
18  
19 would potentially lead to non-accurate conversion between complex graphemes and their  
20  
21 corresponding phonemes: reading the word “yacht” as a whole will lead to accurate reading  
22  
23 whereas processing the same word in sequential parts such as “ya-ch-t” may yield incorrect  
24  
25 phonological decoding (see also Table 1).  
26  
27  
28

29  
30 It would be interesting for future studies to determine (i) whether visual attention span  
31  
32 resources is linked to gamma power (and possible alpha oscillations, see footnote 5), (ii) and  
33  
34 whether a visual attention span reduction and the associated oscillatory underpinnings lead to  
35  
36 more severe dyslexic symptoms in deep compared to shallow orthographies, for which  
37  
38 sequential shifting (theta-gamma coupling) between small grains may be the default visual  
39  
40 attentional processing mode during the early stages of reading acquisition (see Figure 3 and  
41  
42 Table 1).  
43  
44  
45  
46

#### 47 **4. Considerations for clinical practice**

48  
49  
50

---

51  
52 <sup>5</sup> Interestingly, alpha oscillatory activity (around 10 Hz) may have a fundamental role to play in the availability  
53  
54 of gamma activity and the sampling of visual stimuli presented simultaneously (Roux et al., 2012). In particular,  
55  
56 alpha oscillations suppression favors an increase of gamma power for an efficient simultaneous processing of  
57  
58 stimuli (Roux & Ulhaas, 2014). The strength of inhibition of alpha oscillatory activity should also be  
59  
60 proportional to the number of elements that can be processed simultaneously and determine the availability of  
gamma oscillatory power: the higher the number of elements to be processed (e.g., large grain in deep  
orthographies), the stronger the required suppression of alpha activity (Jensen, Gips, Bergmann & Bonnefond,  
2014).

1  
2  
3 Overall, the present framework presents two attentional-oscillatory mechanisms important for  
4 learning to read, and operating in both the visual and the auditory modalities: 1) parsing  
5 mechanisms in the delta and theta ranges (and their coupling) would be in charge of  
6 delimiting phonemic and orthographic chunks through spatiotemporal attentional shifting,  
7 and 2) the content of the parsed chunks falling under the attentional focus would be sampled  
8 via gamma-related activity for further identification. Dyslexia may be associated with deficits  
9 on these two oscillatory-attentional mechanisms (i.e., sluggish attentional shifting and/or  
10 lower focusing resources) in the visual modality, the auditory modality, or both. Importantly,  
11 we argued that the manifestations of these attentional-oscillatory deficits depend on the  
12 linguistic properties of the language(s) learned.  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26

#### 27 **4.1. Explaining and managing the heterogeneity of dyslexia at the individual level:**

##### 28 **Cognitive and reading dyslexic subtypes**

29  
30  
31 Any general neurobiological account of dyslexia should try to explain reading  
32 behavior at the individual level. In this section, we attempt to formulate (when possible) some  
33 predictions regarding the impact of specific oscillatory dysfunctions on the manifestations of  
34 dyslexia across languages in order to explain the heterogeneity of the disorder. In order to  
35 facilitate the diagnosis and management of dyslexia, classification of the disorder in  
36 subgroups has been proposed based on dual route models and single item reading profiles  
37 (e.g., Valdois et al., 2003). Case studies showed the existence of two distinct reading profiles,  
38 namely phonological and surface dyslexia. Prototypical cases of phonological dyslexia reflect  
39 selective difficulties in pseudoword reading but relatively preserved irregular<sup>6</sup> word reading.  
40 Prototypical cases of surface dyslexia are associated with the opposite reading pattern:  
41 preserved pseudoword reading but impaired irregular word (i.e., word that includes irregular  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56

57  
58 <sup>6</sup> In shallow orthographies, word versus pseudoword reading distinction is used as irregular words don't exist.  
59  
60

1  
2  
3 grapheme-to-phoneme mappings) reading. Interestingly, pure phonological and surface  
4  
5 dyslexia are much less common than the mixed subtype, which might in part stem from the  
6  
7 fact that distinct cognitive disorders can lead to similar mixed dyslexia profiles  
8  
9 (Zoubrinetzky, Bielle, & Valdois, 2014).  
10

11  
12 Indeed, other types of classification based on the cognitive disorders associated to  
13  
14 dyslexia have been proposed. In particular, Bosse et al. (2007) suggest that some dyslexic  
15  
16 cases may be associated with a visual attention span disorder, regardless of phonological  
17  
18 deficits (see also Peyrin et al., 2012; Valdois et al., 2003; Zoubrinetzky, Collet, Serniclaes,  
19  
20 Nguyen-Morel, & Valdois, 2016). More recently, Franceschini, Gori, Ruffino, Pedrolli, and  
21  
22 Facoetti (2012) proposed that visuo-spatial attentional orienting difficulties might define  
23  
24 another cognitive subtype of dyslexia, independent from dyslexia associated with  
25  
26 phonological deficits. Importantly, the multi-temporal resolution approach could account for  
27  
28 these three possibly independent cognitive subtypes of dyslexia. In addition, our framework  
29  
30 also suggests that phonological disorders might be split into two phonology-related  
31  
32 constructs, i.e., rhythm/prosodic analysis, and phonemic analysis (see Figure 5.A.). Overall,  
33  
34 we suggest that tasks assessing these four cognitive skills should be systematically included  
35  
36 in dyslexia screening batteries. Some suggestions of what these tasks could be are presented  
37  
38 in Figure 5. B.  
39  
40  
41

42  
43 ---FIGURE 5---  
44  
45

46  
47 In the two following sections, putative links between dyslexic reading and cognitive  
48  
49 subtypes and atypical oscillatory functions are proposed (see Figure 5.A.). We also attempt  
50  
51 to predict how cross-linguistic differences might modulate the manifestation of these dyslexic  
52  
53 subtypes.  
54  
55

#### 4.1.2 Atypical low frequency oscillatory activity

We expect an isolated deficit of low frequency neural entrainment (i.e., delta, theta or their coupling) to lead to chaotic sequential parsing of information falling under the attentional focus (attentional shifting deficits). These parsing difficulties may exacerbate problems in the acquisition of the contour of auditory and visual words (see how light blue and green lines as well as their coupling shape dark blue information in Figure 1.A. and 4.B.) as well as of the positional information of word constituents (through theta oscillatory activity, e.g., Lisman & Jensen, 2013).

In the auditory modality, these problems might impede auditory word learning through a poor analysis of prosodic syllabic contour of words as well as a weak encoding of syllable positions within words. Poor auditory word form representations are likely to have a severe impact on word reading particularly (Ziegler et al., 2014) and be associated with low vocabulary as well as low phonological short term memory skills. These deficits might be exacerbated in languages with unpredictable lexical stress for which stress should be encoded as part of the phonological lexical representations (see Figure 2).

In the visual modality, difficulties in directing the attentional focus to relevant orthographic units should generate fuzzy representations of the visual contour of orthographic units (delta-theta coupling). These problems should strongly perturb pseudoword reading because of impaired graphemic and syllabic parsing, that would in turn affect lexical reading. In addition, difficulties in coding the position of these units within words may be found possibly driven by atypical theta oscillations. Letter position errors may frequently be found in this case (Boros et al., 2016), especially in shallow orthographies where visual theta entrainment may play an important role for reading acquisition (cf Table 1).

A selective deficit at low frequency bands might also trigger negative consequences on gamma oscillatory activity through hierarchical cross-frequency coupling. In that case, the

1  
2  
3 sampling and identification of the attended phonemes and letters should be impaired.  
4  
5 Difficulties in phonemic awareness and letter-sound conversion should be evident, generating  
6  
7 pseudoword reading deficits. These deficits may be exacerbated in deep orthographies  
8  
9 (Landerl et al., 2012) and in languages whose phonotactics prompts the use of small  
10  
11 phonological grains (such as the presence of complex consonantal phonological clusters).  
12  
13

#### 14 15 16 4.1.3 Atypical high frequency oscillatory activity 17

18 We suspect that if neural oscillatory activity is selectively impaired in the gamma  
19  
20 band (aside from cross-frequency coupling issues), the representations words' contour may  
21  
22 be partially preserved but readers should have difficulties in decoding fine-grain orthographic  
23  
24 and/or phonemic contents (dark blue lines in Figures 1 and 4.B). Such selective oscillatory  
25  
26 sampling deficits reflected in the gamma band would cause difficulties in phonemic  
27  
28 awareness and learning letter-sound correspondences, yielding severe problems for  
29  
30 pseudoword reading in particular. Frequent and familiar word reading may be spared through  
31  
32 the use of analogies and logographic strategies that would rely on the visual analysis of word  
33  
34 forms. These deficits may be exacerbated in deep orthographies (Landerl et al., 2012).  
35  
36  
37

38 Lastly, we want to consider possible selective visual deficits associated with abnormal  
39  
40 gamma activity (or the quantity of attentional resources available to process attended units).  
41  
42 We suspect that low gamma power oscillations (potentially caused by poor alpha oscillatory  
43  
44 control, see Footnote 5) may be related to problems in deploying visual attention over letter  
45  
46 strings homogeneously. Such deficit would be associated with a visual attention span disorder  
47  
48 (Bosse et al., 2007) but not necessarily to phonological processing disorders. These  
49  
50 difficulties would preferentially affect reading words as well as items containing complex  
51  
52 multi-letter graphemes (including pseudowords). These deficits may be exacerbated in deep  
53  
54 orthographies. These deficits may be exacerbated in deep  
55  
56 orthographies.  
57  
58  
59  
60



#### 4.1.3. A word of caution for the diagnosis and remediation of dyslexia.

The observation of one specific dyslexic symptom should not be taken as a direct evidence for a specific underlying oscillatory dysfunction. In fact, we predict that distinct oscillatory dysfunctions might lead to relatively similar reading profiles where both word and pseudoword reading might be impaired. We also recommend systematically assessing cognitive abilities as well as taking into account the language background of the individual in order to be able to make an accurate diagnosis and improve the efficacy of intervention programs (Lobier & Valdois, 2014). Some theoretically-based intervention programs have been proposed to train the four cognitive abilities described in Figure 5.A.: action videogames aimed at improving visuo-spatial attentional skills (Franceschini, Gori, Ruffino, Viola, Molteni, & Facoetti, 2013), music intervention to remediate rhythmic and prosodic deficits (Bhide, Power, & Goswami, 2013), visual attention span intervention based on multi-element processing training (Valdois et al., 2014), and letter-sound knowledge intervention to improve phonemic analysis (Kyle, Kujala, Richardson, Lyytinen, & Goswami, 2013; Shaywitz et al., 2004). All of these cognitive interventions yielded significant reading gains in the trained groups suggesting their possible causal role in dyslexia. However, before validating their use in clinical practice, additional carefully designed intervention studies in larger dyslexic populations are further needed (in particular for visual attention-related interventions, e.g., Bavelier, Green, & Seidenberg, 2013; Goswami, 2015b).

## 4.2. Dyslexia in bilinguals

Cross-linguistic research should start considering more seriously the study of bilingual children with dyslexia, since the number of children learning to speak or read in two languages is constantly increasing. Bilingualism is often hard to handle for clinicians because

1  
2  
3 of difficulties disentangling language and reading deficits from language proficiency and  
4  
5 exposure issues. However, guidelines for bilingual dyslexia assessment are scarce, and the  
6  
7 extent to which practitioners should rely on monolingual normative batteries to assess their  
8  
9 bilingual patients remains unclear. A concrete example will be illustrating below  
10  
11 demonstrating how the present framework can help formulate predictions regarding the  
12  
13 manifestations of dyslexia in bilinguals.  
14  
15

16 Let's take the case of Spanish-English bilingualism and visual gamma-related activity.  
17  
18 English orthography is deep and Spanish is shallow. In English monolinguals, gamma  
19  
20 oscillatory power should be optimal in order to cope with large orthographic grains, whereas  
21  
22 Spanish orthography would impose fewer demands on gamma oscillatory power to learn to  
23  
24 read (cf Table 1 and Figure 4). Bilinguals who learn two languages *simultaneously* (speak  
25  
26 and read) have been shown to use a hybrid bilingual orthographic grain size when reading  
27  
28 (Lallier et al., 2013; Lallier et al., 2016). Therefore, simultaneous Spanish-English bilinguals  
29  
30 may use a "medium" visual grain size that would correspond to the average between the large  
31  
32 English and small Spanish grain sizes. This bilingual hybrid grain might boost reading  
33  
34 acquisition in Spanish (in particular lexical reading strategies) but slightly delay it in English,  
35  
36 at least at the early stages of reading acquisition (Lallier et al., 2016). Dyslexic bilinguals  
37  
38 with atypically low gamma power might exhibit fewer reading difficulties in Spanish than in  
39  
40 English compared to their monolingual peers: exposure to English might boost visual  
41  
42 gamma-related skills which might allow them to compensate for their visual deficit when  
43  
44 reading in Spanish.  
45  
46  
47  
48

49 In principle, linguistic interactions could be predicted for all the oscillatory  
50  
51 mechanisms described, if one first carefully identifies the phonological and orthographic  
52  
53 properties specific to the languages learned. Moreover, the manifestations of linguistic  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 interactions in reading should be modulated by the amount of bilingual exposure, i.e., being  
4  
5 more visible in simultaneous than in sequential bilinguals when compared to monolinguals.  
6  
7

## 8 9 10 **5. Conclusion**

11 We proposed novel ideas that should help research determine whether and how both  
12 audio-phonological and visuo-orthographic specifics of a language shape reading  
13 development and modulate atypical auditory and visual neural oscillatory activity at slow and  
14 fast rates in dyslexia. We hope to have demonstrated that operationalizing both *audio-*  
15 phonological and *visuo-*orthographic specifics of language(s) will significantly inform  
16 clinical practice, at least in alphabetic languages. Future research should determine whether  
17 and how the current framework could apply to dyslexia in logographic writing systems and  
18 tonal languages.  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28

29 A first step to test our cross-linguistic hypotheses would be to directly compare dyslexic  
30 groups speaking languages that vary on the aforementioned language specifics on their visual  
31 and auditory oscillatory activity elicited by the passive perception of non-linguistic stimuli  
32 presented at various frequency bands, i.e., amplitude modulated white noises and visual  
33 flickering dots. Coupling eye movement and electrophysiological recordings during visual  
34 search should also be a promising design to test the visual oscillatory reading framework.  
35  
36  
37  
38  
39  
40  
41  
42

43 Because of their non-linguistic and/or passive nature, these tasks could ideally be  
44 administered longitudinally in children before learning to read until afterwards, and test the  
45 causal role of neural entrainment in reading development and dyslexia (Goswami et al.,  
46 2014). It may then be found that, in some cases, these language specifics have a negative  
47 impact on the manifestations of atypical neural sampling in dyslexia, whereas, in other cases,  
48 they may help the system compensate for some deficits. Consequently, a careful look should  
49 be taken at how some of these different manifestations of dyslexia may put individuals at  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 greater risk for other atypical phenotypes such as, for example, specific language  
4 impairments, since genetic research shows that both disorders share some biological bases  
5  
6  
7 (Newbury et al., 2011).  
8

9  
10 We provided here some first hints on a range of questions that research will need to  
11 investigate further in the years to come.  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For Peer Review

### Acknowledgments

This research was funded by the European Research Council (ERC advanced grant, BILITERACY project, to M.C.), and the Spanish Government (Plan Nacional-PSI2012-32128 and PSI2015-65338-P to M.L, Plan Nacional-PSI2012-32350 and PSI2015-65694-P to N.M. and Plan Nacional- PSI2015-67353-R to M. C.). BCBL acknowledges funding from Ayuda Centro de Excelencia Severo Ochoa SEV-2015-0490. We are thankful for the comments of three anonymous reviewers on the previous versions of the manuscript.

For Peer Review

## References

- Abrams, D. A., Nicol, T., Zecker, S., & Kraus, N. (2009). Abnormal cortical processing of the syllable rate of speech in poor readers. *The Journal of Neuroscience*, 29(24), 7686-7693.
- Bavelier, D., Green, C. S., & Seidenberg, M. S. (2013). Cognitive development: gaming your way out of dyslexia?. *Current Biology*, 23(7), R282-R283.
- Boets, B., de Beeck, H. P. O., Vandermosten, M., Scott, S. K., Gillebert, C. R., Mantini, D et al (2013). Intact but less accessible phonetic representations in adults with dyslexia. *Science*, 342(6163), 1251-1254.
- Bhide, A., Power, A., & Goswami, U. (2013). A rhythmic musical intervention for poor readers: A comparison of efficacy with a letter-based intervention. *Mind, Brain, and Education*, 7(2), 113-123.
- Bishop, D. V., & Snowling, M. J. (2004). Dyslexia and specific language impairment: Same or different?. *Psychological bulletin*, 130(6), 858.
- Brem, S., Bach, S., Kucian, K., Guttorm, T. K., Martin, E., Lyytinen, H., et al. (2010). Brain sensitivity to print emerges when children learn letter–speech sound correspondences. *Proceedings of the National Academy of Sciences*, 107(17), 7939-7944.
- Boros, M., Anton, J. L., Pech-Georgel, C., Grainger, J., Szwed, M., & Ziegler, J. C. (2016). Orthographic processing deficits in developmental dyslexia: Beyond the ventral visual stream. *NeuroImage*, 128, 316-327.
- Bosman, C. A., Womelsdorf, T., Desimone, R., & Fries, P. (2009). A microsaccadic rhythm modulates gamma-band synchronization and behavior. *The Journal of Neuroscience*, 29(30), 9471-9480.
- Bosse, M. L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition*, 104(2), 198-230.

- 1  
2  
3 Bosse, M. L., & Valdois, S. (2009). Influence of the visual attention span on child reading  
4  
5 performance: a cross-sectional study. *Journal of Research in Reading*, 32(2), 230-253.  
6  
7 Bundesen, C., Habekost, T., & Kyllingsbæk, S. (2005). A neural theory of visual attention:  
8  
9 bridging cognition and neurophysiology. *Psychological review*, 112(2), 291.  
10  
11 Busch, N. A., & VanRullen, R. (2010). Spontaneous EEG oscillations reveal periodic  
12  
13 sampling of visual attention. *Proceedings of the National Academy of Sciences*,  
14  
15 107(37), 16048-16053.  
16  
17  
18 Busch, N., & VanRullen, R. (2014). Is visual perception like a continuous flow or a series of  
19  
20 snapshots. *Subjective time: The philosophy, psychology, and neuroscience of*  
21  
22 *temporality*, 161-178.  
23  
24  
25 Calderone, D. J., Lakatos, P., Butler, P. D., & Castellanos, F. X. (2014). Entrainment of  
26  
27 neural oscillations as a modifiable substrate of attention. *Trends in cognitive sciences*,  
28  
29 18(6), 300-309.  
30  
31  
32 Caravolas, M., & Bruck, M. (1993). The Effect of Oral and Written Language Input on  
33  
34 Children's Phonological Awareness: A Cross-Linguistic Study. *Journal of*  
35  
36 *experimental child psychology*, 55(1), 1-30.  
37  
38  
39 Caravolas, M., & Landerl, K. (2010). The influences of syllable structure and reading ability  
40  
41 on the development of phoneme awareness: A longitudinal, cross-linguistic study.  
42  
43 *Scientific Studies of Reading*, 14(5), 464-484.  
44  
45  
46 Christophe, A., Peperkamp, S., Pallier, C., Block, E., & Mehler, J. (2004). Phonological  
47  
48 phrase boundaries constrain lexical access I. Adult data. *Journal of Memory and*  
49  
50 *Language*, 51(4), 523-547.  
51  
52  
53 Curtin, S. (2010). Young infants encode lexical stress in newly encountered words. *Journal*  
54  
55 *of experimental child psychology*, 105(4), 376-385.  
56  
57  
58  
59  
60

- 1  
2  
3 Díaz, B., Hintz, F., Kiebel, S. J., & von Kriegstein, K. (2012). Dysfunction of the auditory  
4  
5 thalamus in developmental dyslexia. *Proceedings of the National Academy of*  
6  
7 *Sciences*, *109*(34), 13841-13846.  
8  
9  
10 Dupoux, E., Pallier, C., Sebastian, N., & Mehler, J. (1997). A distressing “deafness” in  
11  
12 French?. *Journal of Memory and Language*, *36*(3), 406-421.  
13  
14 Dupoux, E., Peperkamp, S., & Sebastián-Gallés, N. (2010). Limits on bilingualism revisited:  
15  
16 Stress ‘deafness’ in simultaneous French–Spanish bilinguals. *Cognition*, *114*(2), 266-  
17  
18 275.  
19  
20  
21 Dupoux, E., Sebastián-Gallés, N., Navarrete, E., & Peperkamp, S. (2008). Persistent stress  
22  
23 ‘deafness’: The case of French learners of Spanish. *Cognition*, *106*(2), 682-706.  
24  
25  
26 Ellis, N. C., & Hooper, A. M. (2001). Why learning to read is easier in Welsh than in  
27  
28 English: Orthographic transparency effects evinced with frequency-matched tests.  
29  
30 *Applied Psycholinguistics*, *22*(04), 571-599.  
31  
32  
33 Facoetti, A., Lorusso, M. L., Cattaneo, C., Galli, R., & Molteni, M. (2005). Visual and  
34  
35 auditory attentional capture are both sluggish in children with developmental  
36  
37 dyslexia. *Acta Neurobiologiae Experimentalis*, *65*(1), 61-72.  
38  
39  
40 Franceschini, S., Gori, S., Ruffino, M., Viola, S., Molteni, M., & Facoetti, A. (2013). Action  
41  
42 video games make dyslexic children read better. *Current Biology*, *23*(6), 462-466.  
43  
44  
45 Franceschini, S., Gori, S., Ruffino, M., Pedrolli, K., & Facoetti, A. (2012). A causal link  
46  
47 between visual spatial attention and reading acquisition. *Current Biology*, *22*(9), 814-  
48  
49 819.  
50  
51 Fawcett, A. J., Nicolson, R. I., & Dean, P. (1996). Impaired performance of children with  
52  
53 dyslexia on a range of cerebellar tasks. *Annals of Dyslexia*, *46*(1), 259-283.  
54  
55  
56 Frith, U. (1986). A developmental framework for dyslexia. *Annals of dyslexia*, *36*(1), 67-81.  
57  
58  
59  
60



- 1  
2  
3 Galaburda, A. M., Menard, M. T., & Rosen, G. D. (1994). Evidence for aberrant auditory  
4 anatomy in developmental dyslexia. *Proceedings of the National Academy of*  
5 *Sciences*, *91*(17), 8010-8013.  
6  
7  
8  
9  
10 Gandour, J., Wong, D., Hsieh, L., Weinzapfel, B., Van Lancker, D., & Hutchins, G. D.  
11 (2000). A crosslinguistic PET study of tone perception. *Journal of cognitive*  
12 *neuroscience*, *12*(1), 207-222.  
13  
14  
15  
16 Gervain, J., & Werker, J. F. (2013). Prosody cues word order in 7-month-old bilingual  
17 infants. *Nature communications*, *4*, 1490.  
18  
19  
20  
21 Giraud, A. L., & Poeppel, D. (2012). Cortical oscillations and speech processing: emerging  
22 computational principles and operations. *Nature neuroscience*, *15*(4), 511-517.  
23  
24  
25 Giraud, A. L., & Ramus, F. (2013). Neurogenetics and auditory processing in dyslexia.  
26 *Current opinion in neurobiology*, *23*(1), 37-42.  
27  
28  
29  
30 Goswami, U. (2011). A temporal sampling framework for dyslexia. *Trends in cognitive*  
31 *sciences*, *15*(1), 3-10.  
32  
33  
34 Goswami, U. (2015a). Sensory theories of developmental dyslexia: three challenges for  
35 research. *Nature Reviews Neuroscience*, *16*(1), 43-54.  
36  
37  
38 Goswami, U. (2015b). Visual attention span deficits and assessing causality in developmental  
39 dyslexia. *Nature Reviews Neuroscience*, *16*(4), 225-226.  
40  
41  
42  
43 Goswami, U., Gerson, D., & Astruc, L. (2010). Amplitude envelope perception, phonology  
44 and prosodic sensitivity in children with developmental dyslexia. *Reading and*  
45 *Writing*, *23*(8), 995-1019.  
46  
47  
48  
49 Goswami, U., Huss, M., Mead, N., Fosker, T., & Verney, J. P. (2013). Perception of patterns  
50 of musical beat distribution in phonological dyslexia: significant longitudinal relations  
51 with word reading and reading comprehension. *Cortex*, *49*(5), 1363-1376.  
52  
53  
54  
55  
56  
57  
58  
59  
60

- 1  
2  
3 Goswami, U., & Leong, V. (2013). Speech rhythm and temporal structure: converging  
4  
5 perspectives. *Laboratory Phonology, 4*, 67-92.  
6  
7 Goswami, U., Power, A. J., Lallier, M., & Facoetti, A. (2014). Oscillatory “temporal  
8  
9 sampling” and developmental dyslexia: toward an over-arching theoretical  
10  
11 framework. *Frontiers in human neuroscience, 8*.  
12  
13 Goswami, U., & Ziegler, J. C. (2006). Fluency, phonology and morphology: a response to the  
14  
15 commentaries on becoming literate in different languages. *Developmental Science,*  
16  
17 *9(5)*, 451-453.  
18  
19  
20  
21 Gross, J., Hoogenboom, N., Thut, G., Schyns, P., Panzeri, S., Belin, P., & Garrod, S. (2013).  
22  
23 Speech rhythms and multiplexed oscillatory sensory coding in the human brain. *PLoS*  
24  
25 *biology, 11(12)*, e1001752.  
26  
27  
28 Guttorm, T. K., Leppänen, P. H., Poikkeus, A. M., Eklund, K. M., Lyytinen, P., & Lyytinen,  
29  
30 H. (2005). Brain event-related potentials (ERPs) measured at birth predict later  
31  
32 language development in children with and without familial risk for dyslexia. *Cortex,*  
33  
34 *41(3)*, 291-303.  
35  
36  
37 Guttorm, T. K., Leppänen, P. H., Richardson, U., & Lyytinen, H. (2001). Event-related  
38  
39 potentials and consonant differentiation in newborns with familial risk for dyslexia.  
40  
41 *Journal of Learning Disabilities, 34(6)*, 534-544.  
42  
43  
44 Hämäläinen, J. A., Rupp, A., Soltész, F., Szücs, D., & Goswami, U. (2012). Reduced phase  
45  
46 locking to slow amplitude modulation in adults with dyslexia: an MEG study.  
47  
48 *Neuroimage, 59(3)*, 2952-2961.  
49  
50  
51 Hari, R., & Parkkonen, L. (2015). The brain timewise: how timing shapes and supports brain  
52  
53 function. *Philosophical Transactions of the Royal Society of London B: Biological*  
54  
55 *Sciences, 370(1668)*, 20140170.  
56  
57  
58  
59  
60

- 1  
2  
3 Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia.  
4  
5 *Trends in cognitive sciences*, 5(12), 525-532.  
6  
7 Hoffman, K. L., Dragan, M. C., Leonard, T. K., Micheli, C., Montefusco-Siegmund, R., &  
8  
9 Valiante, T. A. (2014). Saccades during visual exploration align hippocampal 3–8 Hz  
10  
11 rhythms in human and non-human primates. *Frontiers in Systems Neuroscience*,  
12  
13 7(43), 80-89.  
14  
15 Hood, M., & Conlon, E. (2004). Visual and auditory temporal processing and early reading  
16  
17 development. *Dyslexia*, 10(3), 234-252.  
18  
19 Ito, J., Maldonado, P., & Grün, S. (2014). Cross-frequency interaction of the eye-movement  
20  
21 related LFP signals in V1 of freely viewing monkeys. *Frontiers in Systems*  
22  
23 *Neuroscience*, 7(1), 1-11.  
24  
25  
26  
27 Jednoróg, K., Marchewka, A., Altarelli, I., Monzalvo Lopez, A. K., van Ermingen-Marbach,  
28  
29 M., Grande, M., ... & Ramus, F. (2015). How reliable are gray matter disruptions in  
30  
31 specific reading disability across multiple countries and languages? insights from a  
32  
33 large-scale voxel-based morphometry study. *Human brain mapping*, 36(5), 1741-  
34  
35 1754.  
36  
37  
38 Jensen, O., Gips, B., Bergmann, T. O., & Bonnefond, M. (2014). Temporal coding organized  
39  
40 by coupled alpha and gamma oscillations prioritize visual processing. *Trends in*  
41  
42 *neurosciences*, 37(7), 357-369.  
43  
44  
45 Kashino, M., & Kondo, H. M. (2012). Functional brain networks underlying perceptual  
46  
47 switching: auditory streaming and verbal transformations. *Philosophical Transactions*  
48  
49 *of the Royal Society of London B: Biological Sciences*, 367(1591), 977-987.  
50  
51  
52 Kotz, S. A., & Schmidt-Kassow, M. (2015). Basal ganglia contribution to rule expectancy  
53  
54 and temporal predictability in speech. *Cortex*, 68, 48-60.  
55  
56  
57  
58  
59  
60

- 1  
2  
3 Kotz, S. A., & Schwartz, M. (2010). Cortical speech processing unplugged: a timely  
4  
5 subcortico-cortical framework. *Trends in cognitive sciences*, *14*(9), 392-399.  
6  
7  
8 Kyle, F., Kujala, J., Richardson, U., Lyytinen, H., & Goswami, U. (2013). Assessing the  
9  
10 effectiveness of two theoretically motivated computer-assisted reading interventions  
11  
12 in the United Kingdom: GG Rime and GG Phoneme. *Reading Research Quarterly*,  
13  
14 *48*(1), 61-76.  
15  
16 Lallier, M., Acha, J., & Carreiras, M. (2016). Cross-linguistic interactions influence reading  
17  
18 development in bilinguals: a comparison between early balanced French-Basque and  
19  
20 Spanish-Basque bilingual children. *Developmental science*, *19*(1), 76-89.  
21  
22  
23 Laasonen, M., Tomma-Halme, J., Lahti-Nuutila, P., Service, E., & Virsu, V. (2000). Rate of  
24  
25 information segregation in developmentally dyslexic children. *Brain and Language*,  
26  
27 *75*(1), 66-81.  
28  
29  
30 Laasonen, M., & Virsu, V. J. (2001). Temporal order and processing acuity of visual,  
31  
32 auditory, and tactile perception in developmentally dyslexic young adults. *Cognitive*,  
33  
34 *Affective, & Behavioral Neuroscience*, *1*(4), 394-410.  
35  
36  
37 Lallier, M., Carreiras, M., Tainturier, M. J., Savill, N., & Thierry, G. (2013). Orthographic  
38  
39 transparency modulates the grain size of orthographic processing: behavioral and ERP  
40  
41 evidence from bilingualism. *Brain research*, *1505*, 47-60.  
42  
43  
44 Lallier, M., Donnadieu, S., Berger, C., & Valdois, S. (2010). A case study of developmental  
45  
46 phonological dyslexia: Is the attentional deficit in the perception of rapid stimuli  
47  
48 sequences amodal?. *cortex*, *46*(2), 231-241.  
49  
50  
51 Lallier, M., Donnadieu, S., & Valdois, S. (2013a). Developmental dyslexia: exploring how  
52  
53 much phonological and visual attention span disorders are linked to simultaneous  
54  
55 auditory processing deficits. *Annals of dyslexia*, *63*(2), 97-116.  
56  
57  
58  
59  
60

- 1  
2  
3 Lallier, M., Donnadieu, S., & Valdois, S. (2013b). Investigating the role of visual and  
4  
5 auditory search in reading and dyslexia. *Frontiers in human neuroscience*, 7.  
6  
7 Lallier, M., Tainturier, M. J., Dering, B., Donnadieu, S., Valdois, S., & Thierry, G. (2010).  
8  
9 Behavioral and ERP evidence for amodal sluggish attentional shifting in  
10  
11 developmental dyslexia. *Neuropsychologia*, 48(14), 4125-4135.  
12  
13 Lallier, M., Thierry, G., & Tainturier, M. J. (2013). On the importance of considering  
14  
15 individual profiles when investigating the role of auditory sequential deficits in  
16  
17 dyslexia. *Cognition*, 126(1), 121-127.  
18  
19 Lallier, M., Thierry, G., Tainturier, M. J., Donnadieu, S., Peyrin, C., Billard, C., & Valdois,  
20  
21 S. (2009). Auditory and visual stream segregation in children and adults: an  
22  
23 assessment of the amodality assumption of the 'sluggish attentional shifting' theory of  
24  
25 dyslexia. *Brain research*, 1302, 132-147.  
26  
27 Lallier, M., & Valdois, S. (2012). Sequential vs simultaneous processing deficits in dyslexia.  
28  
29 *Dyslexia-A Comprehensive and International Approach*, 73-108.  
30  
31 Landerl, K., Ramus, F., Moll, K., Lyytinen, H., Leppänen, P. H., Lohvansuu, K, et al. (2013).  
32  
33 Predictors of dyslexia in European orthographies with varying complexity. *Journal of*  
34  
35 *Child Psychology and Psychiatry*, 54(6), 686-694.  
36  
37 Lehongre, K., Morillon, B., Giraud, A. L., & Ramus, F. (2013). Impaired auditory sampling  
38  
39 in dyslexia: further evidence from combined fMRI and EEG. *Frontiers in human*  
40  
41 *neuroscience*, 7.  
42  
43 Lehongre, K., Ramus, F., Villiermet, N., Schwartz, D., & Giraud, A. L. (2011). Altered low-  
44  
45 gamma sampling in auditory cortex accounts for the three main facets of dyslexia.  
46  
47 *Neuron*, 72(6), 1080-1090.  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

- 1  
2  
3 Leong, V., Kalashnikova, M., Burnham, D., & Goswami, U. (2014, September). Infant-  
4  
5 directed speech enhances temporal rhythmic structure in the envelope. In *Interspeech*  
6  
7 (pp. 2563-2567).  
8  
9  
10 Livingstone, M. S., Rosen, G. D., Drislane, F. W., & Galaburda, A. M. (1991). Physiological  
11  
12 and anatomical evidence for a magnocellular defect in developmental dyslexia.  
13  
14 *Proceedings of the National Academy of Sciences*, 88(18), 7943-7947  
15  
16 Lisman, J. E., &  
17 Jensen, O. (2013). The theta-gamma neural code. *Neuron*, 77(6), 1002-1016.  
18  
19 Lizarazu, M., Lallier, M., Molinaro, N., Bourguignon, M., Paz-Alonso, P. M.,  
20  
21 Lerma-Usabiaga, G., & Carreiras, M. (2015). Developmental evaluation of atypical  
22  
23 auditory sampling in dyslexia: Functional and structural evidence. *Human brain*  
24  
25 *mapping*, 36(12), 4986-5002.  
26  
27  
28 Lobier, M., Zoubrinetzky, R., & Valdois, S. (2012). The visual attention span deficit in  
29  
30 dyslexia is visual and not verbal. *Cortex*, 48(6), 768-773.  
31  
32  
33 Lobier, M., & Valdois, S. (2009). Prise en charge des dyslexies développementales: critères  
34  
35 d'évaluation. *Revue de neuropsychologie*, 1(2), 102-109.  
36  
37  
38 Meyler, A., & Breznitz, Z. (2005). Visual, auditory and cross-modal processing of linguistic  
39  
40 and nonlinguistic temporal patterns among adult dyslexic readers. *Dyslexia*, 11(2), 93-  
41  
42 115.  
43  
44  
45 Molinaro, N., Canal, P., Vespignani, F., Pesciarelli, F., & Cacciari, C. , (2013) Are complex  
46  
47 function words processed as semantically empty strings? A reading time and ERP  
48  
49 study of Collocational Complex Prepositions. *Language and Cognitive Processes*, 28  
50  
51 (6), 762-788. DOI: 10.1080/01690965.2012.665465.  
52  
53  
54 Molinaro, N., Vespignani, F., Canal, P., Fonda, S., & Cacciari, C. , (2008) Cloze-probability  
55  
56 does not only affect N400 amplitude: The case of complex prepositions.  
57  
58  
59  
60

- 1  
2  
3 Molinaro, N., Lizarazu, M., Lallier, M., Bourguignon, M., & Carreiras, M. (2016).  
4  
5 Out-of-synchrony speech entrainment in developmental dyslexia. *Human Brain*  
6  
7 *Mapping*.  
8  
9  
10 Molnar, M., Lallier, M., & Carreiras, M. (2014). The amount of language exposure  
11  
12 determines nonlinguistic tone grouping biases in infants from a bilingual  
13  
14 environment. *Language Learning*, 64(s2), 45-64.  
15  
16  
17 Nespor, M., Shukla, M., van de Vijver, R., Avesani, C., Schraudolf, H., & Donati, C. (2008).  
18  
19 Different phrasal prominence realization in VO and OV languages. *Lingue e*  
20  
21 *Linguaggio*, 7(2), 1-28.  
22  
23  
24 Newbury, D. F., Paracchini, S., Scerri, T. S., Winchester, L., Addis, L., Richardson, A. J., ...  
25  
26 & Monaco, A. P. (2011). Investigation of dyslexia and SLI risk variants in reading-  
27  
28 and language-impaired subjects. *Behavior genetics*, 41(1), 90-104.  
29  
30  
31 Nicolson, R. I., Fawcett, A. J., & Dean, P. (2001). Developmental dyslexia: the cerebellar  
32  
33 deficit hypothesis. *Trends in neurosciences*, 24(9), 508-511.  
34  
35  
36 Panzeri, S., Brunel, N., Logothetis, N. K., & Kayser, C. (2010). Sensory neural codes using  
37  
38 multiplexed temporal scales. *Trends in neurosciences*, 33(3), 111-120.  
39  
40  
41 Park, H., Ince, R. A., Schyns, P. G., Thut, G., & Gross, J. (2015). Frontal top-down signals  
42  
43 increase coupling of auditory low-frequency oscillations to continuous speech in  
44  
45 human listeners. *Current Biology*, 25(12), 1649-1653.  
46  
47  
48 Pennington, B. F., & Lefly, D. L. (2001). Early reading development in children at family  
49  
50 risk for dyslexia. *Child development*, 72(3), 816-833.  
51  
52  
53 Peperkamp, S., Vendelin, I., & Dupoux, E. (2010). Perception of predictable stress: A cross-  
54  
55 linguistic investigation. *Journal of Phonetics*, 38(3), 422-430.  
56  
57  
58  
59  
60

- 1  
2  
3 Pernet, C. R., Poline, J. B., Demonet, J. F., & Rousselet, G. A. (2009). Brain classification  
4  
5 reveals the right cerebellum as the best biomarker of dyslexia. *BMC neuroscience*,  
6  
7 *10*(1), 67.  
8  
9  
10 Power, A. J., Colling, L. J., Mead, N., Barnes, L., & Goswami, U. (2016). Neural encoding of  
11  
12 the speech envelope by children with developmental dyslexia. *Brain and Language*,  
13  
14 *160*, 1-10.  
15  
16 Protopapas, A. (2014). From temporal processing to developmental language disorders: mind  
17  
18 the gap. *Philosophical Transactions of the Royal Society B: Biological Sciences*,  
19  
20 *369*(1634), 20130090.  
21  
22  
23 Pugh, K. R., Landi, N., Preston, J. L., Mencl, W. E., Austin, A. C., Sibley, D., ... & Molfese,  
24  
25 P. (2013). The relationship between phonological and auditory processing and brain  
26  
27 organization in beginning readers. *Brain and language*, *125*(2), 173-183.  
28  
29  
30 Quené, H., & Port, R. (2005). Effects of timing regularity and metrical expectancy on  
31  
32 spoken-word perception. *Phonetica*, *62*(1), 1-13.  
33  
34 Radanovic, M., Azambuja, M., Mansur, L. L., Porto, C. S., & Scaff, M. (2003). Thalamus  
35  
36 and language: interface with attention, memory and executive functions. *Arquivos de*  
37  
38 *neuro-psiquiatria*, *61*(1), 34-42.  
39  
40  
41 Ramus, F. (2014). Neuroimaging sheds new light on the phonological deficit in dyslexia.  
42  
43 *Trends in cognitive sciences*, *18*(6), 274-275.  
44  
45  
46 Ramus, F., & Ahissar, M. (2012). Developmental dyslexia: The difficulties of interpreting  
47  
48 poor performance, and the importance of normal performance. *Cognitive*  
49  
50 *Neuropsychology*, *29*(1-2), 104-122.  
51  
52  
53 Ramus, F., Nespors, M., & Mehler, J. (1999). Correlates of linguistic rhythm in the speech  
54  
55 signal. *Cognition*, *73*(3), 265-292.  
56  
57  
58  
59  
60



- 1  
2  
3 Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., et al. (2003).  
4  
5 Theories of developmental dyslexia: insights from a multiple case study of dyslexic  
6  
7 adults. *Brain*, *126*(4), 841-865.  
8  
9  
10 Ramus, F., & Szenkovits, G. (2008). What phonological deficit?. *The Quarterly Journal of*  
11  
12 *Experimental Psychology*, *61*(1), 129-141.  
13  
14 Rau, A. K., Moll, K., Snowling, M. J., & Landerl, K. (2015). Effects of orthographic  
15  
16 consistency on eye movement behavior: German and English children and adults  
17  
18 process the same words differently. *Journal of experimental child psychology*, *130*,  
19  
20 92-105.  
21  
22  
23 Rayner, K. (1998). Eye movements in reading and information processing: 20 years of  
24  
25 research. *Psychological bulletin*, *124*(3), 372.  
26  
27  
28 Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in  
29  
30 reading disabled children. *Journal of experimental child psychology*, *48*(2), 270-292.  
31  
32  
33 Richlan, F. (2014). Functional neuroanatomy of developmental dyslexia: the role of  
34  
35 orthographic depth. *Frontiers in human neuroscience*, *8*, 347.  
36  
37  
38 Roth, M. J., Synofzik, M., & Lindner, A. (2013). The cerebellum optimizes perceptual  
39  
40 predictions about external sensory events. *Current Biology*, *23*(10), 930-935.  
41  
42  
43 Roux, F., & Uhlhaas, P. J. (2014). Working memory and neural oscillations: alpha–gamma  
44  
45 versus theta–gamma codes for distinct WM information?. *Trends in cognitive*  
46  
47 *sciences*, *18*(1), 16-25.  
48  
49  
50 Roux, F., Wibrals, M., Mohr, H. M., Singer, W., & Uhlhaas, P. J. (2012). Gamma-band  
51  
52 activity in human prefrontal cortex codes for the number of relevant items maintained  
53  
54 in working memory. *The Journal of neuroscience*, *32*(36), 12411-12420.  
55  
56  
57 Shaywitz, B. A., Shaywitz, S. E., Blachman, B. A., Pugh, K. R., Fulbright, R. K., Skudlarski,  
58  
59 P., ... & Fletcher, J. M. (2004). Development of left occipitotemporal systems for  
60

- 1  
2  
3 skilled reading in children after a phonologically-based intervention. *Biological*  
4  
5 *psychiatry*, 55(9), 926-933.  
6  
7 Schmalz, X., Marinus, E., Coltheart, M., & Castles, A. (2015). Getting to the bottom of  
8  
9 orthographic depth. *Psychonomic bulletin & review*, 22(6), 1614-1629.  
10  
11 Schwartz, M., Keller, P. E., & Kotz, S. A. (2016). Spontaneous, synchronized, and  
12  
13 corrective timing behavior in cerebellar lesion patients. *Behavioural Brain Research*,  
14  
15 312, 285-293.  
16  
17 Scott, S. K., & McGettigan, C. (2013). Do temporal processes underlie left hemisphere  
18  
19 dominance in speech perception?. *Brain and language*, 127(1), 36-45.  
20  
21 Seidenberg, M. S. (2011). What causes dyslexia?: comment on Goswami. *Trends in cognitive*  
22  
23 *sciences*, 15(1), 2.  
24  
25  
26  
27 Seymour, P. H., Aro, M., & Erskine, J. M. (2003). Foundation literacy acquisition in  
28  
29 European orthographies. *British Journal of psychology*, 94(2), 143-174.  
30  
31 Skoruppa, K., Pons, F., Bosch, L., Christophe, A., Cabrol, D., & Peperkamp, S. (2013). The  
32  
33 development of word stress processing in French and Spanish infants. *Language*  
34  
35 *Learning and Development*, 9(1), 88-104.  
36  
37  
38 Snowling, M. J. (2008). Specific disorders and broader phenotypes: The case of dyslexia.  
39  
40 *The Quarterly Journal of Experimental Psychology*, 61(1), 142-156.  
41  
42  
43 Snowling, M. J. (1981). Phonemic deficits in dyslexia. *Psychological research*, 43(2), 219-  
44  
45 234.  
46  
47 Soroli, E., Szenkovits, G., & Ramus, F. (2010). Exploring dyslexics' phonological deficit III:  
48  
49 foreign speech perception and production. *Dyslexia*, 16(4), 318-340.  
50  
51 Sprenger-Charolles, L., & Colé, P. (2013). *Lecture et dyslexie. Approche cognitive. (2e ed.*  
52  
53 *rév.). Paris : Dunod.*  
54  
55  
56 Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia*, 7(1), 12-36.  
57  
58  
59  
60

- 1  
2  
3 Stein, J., & Talcott, J. (1999). Impaired neuronal timing in dyslexia—the magnocellular  
4  
5 hypothesis. *Dyslexia*, 5(2), 59.  
6  
7 Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia.  
8  
9 *Trends in neurosciences*, 20(4), 147-152.  
10  
11 Stoodley, C. J. (2015). The Role of the Cerebellum in Developmental Dyslexia. *The*  
12  
13 *Linguistic Cerebellum*, 199.  
14  
15 Stoodley, C. J., Fawcett, A. J., Nicolson, R. I., & Stein, J. F. (2006). Balancing and pointing  
16  
17 tasks in dyslexic and control adults. *Dyslexia*, 12(4), 276-288.  
18  
19 Stoodley, C. J., Harrison, E. P., & Stein, J. F. (2006). Implicit motor learning deficits in  
20  
21 dyslexic adults. *Neuropsychologia*, 44(5), 795-798.  
22  
23 Stoodley, C. J., & Stein, J. F. (2011). The cerebellum and dyslexia. *Cortex*, 47(1), 101-116.  
24  
25 Stoodley, C. J., & Stein, J. F. (2013). Cerebellar function in developmental dyslexia. *The*  
26  
27 *Cerebellum*, 12(2), 267-276.  
28  
29 Szalkowski, C. E., Booker, A. B., Truong, D. T., Threlkeld, S. W., Rosen, G. D., & Fitch, R.  
30  
31 H. (2013). Knockdown of the candidate dyslexia susceptibility gene homolog *Dyx1c1*  
32  
33 in rodents: Effects on auditory processing, visual attention, and cortical and thalamic  
34  
35 anatomy. *Developmental neuroscience*, 35(1), 50-68.  
36  
37 Szczepanski, S. M., Crone, N. E., Kuperman, R. A., Auguste, K. I., Parvizi, J., & Knight, R.  
38  
39 T. (2014). Dynamic changes in phase-amplitude coupling facilitate spatial attention  
40  
41 control in fronto-parietal cortex. *PLoS Biol*, 12(8), e1001936.  
42  
43 Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children.  
44  
45 *Brain and language*, 9(2), 182-198.  
46  
47 Teki, S., Grube, M., Kumar, S., & Griffiths, T. D. (2011). Distinct neural substrates of  
48  
49 duration-based and beat-based auditory timing. *The Journal of Neuroscience*, 31(10),  
50  
51 3805-3812.  
52  
53  
54  
55  
56  
57  
58  
59  
60

- 1  
2  
3 Valdois, S., Peyrin, C., Lassus-Sangosse, D., Lallier, M., Démonet, J. F., & Kandel, S.  
4  
5 (2014). Dyslexia in a French–Spanish bilingual girl: behavioural and neural  
6  
7 modulations following a visual attention span intervention. *Cortex*, *53*, 120-145.  
8  
9  
10 VanRullen, R., Carlson, T., & Cavanagh, P. (2007). The blinking spotlight of attention.  
11  
12 *Proceedings of the National Academy of Sciences*, *104*(49), 19204-19209.  
13  
14 Vidyasagar, T. R. (2013). Reading into neuronal oscillations in the visual system:  
15  
16 implications for developmental dyslexia.  
17  
18 Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: a deficit in visuo-spatial attention, not in  
19  
20 phonological processing. *Trends in cognitive sciences*, *14*(2), 57-63.  
21  
22  
23 White, L., & Mattys, S. L. (2007). Calibrating rhythm: First language and second language  
24  
25 studies. *Journal of Phonetics*, *35*(4), 501-522.  
26  
27  
28 Winkler, I., Denham, S. L., & Nelken, I. (2009). Modeling the auditory scene: predictive  
29  
30 regularity representations and perceptual objects. *Trends in cognitive sciences*, *13*(12),  
31  
32 532-540.  
33  
34 Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, dyslexia, and skilled reading  
35  
36 across languages: a psycholinguistic grain size theory. *Psychological bulletin*, *131*(1),  
37  
38 3.  
39  
40 Ziegler, J. C., Perry, C., & Zorzi, M. (2014). Modelling reading development through  
41  
42 phonological decoding and self-teaching: implications for dyslexia. *Philosophical*  
43  
44 *Transactions of the Royal Society of London B: Biological Sciences*, *369*(1634),  
45  
46 20120397.  
47  
48  
49 Zoubrinetzky, R., Bielle, F., & Valdois, S. (2014). New insights on developmental dyslexia  
50  
51 subtypes: heterogeneity of mixed reading profiles. *PloS one*, *9*(6), e99337.  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 Zoubrinetzky, R., Collet, G., Serniclaes, W., Nguyen-Morel, M. A., & Valdois, S. (2016).  
4

5 Relationships between Categorical Perception of Phonemes, Phoneme Awareness,  
6

7 and Visual Attention Span in Developmental Dyslexia. *PloS one*, *11*(3), e0151015.  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For Peer Review

## Glossary

**Amplitude (power):** refers to the magnitude of an oscillation. In neural oscillation, amplitude is interpreted as reflecting the linear summation of the spike trains of neuronal populations whose rhythmic activity can be highly synchronized (eliciting larger amplitude) or desynchronized (lower amplitude).

**Attentional shifting:** reflects a mechanism through which attentional resources are directed to a point in time or space to facilitate the processing of this information. This implies that the allocation of attention to irrelevant information is decreased (inhibition). In the visual modality, overt attentional shifting occurs when the eyes are moving, whereas covert attentional shifting does not and can happen while the eyes remain fixated on a specific point.

**Grain size:** refers to the size of the units that will be relevant for phonological and orthographic information processing. A large grain will correspond to multiple letter/phoneme units whereas small grains may typically correspond to single letter/phoneme. Moreover, grain size will vary depending on the type of orthography (deep or shallow), the reading developmental stage (early or late), or the type of item to be read (e.g., new or familiar word, consistent or inconsistent word).

**Graphemes:** correspond to the smallest units of a written language. These written units correspond to the phonemic oral units. Graphemes better reflect the phonology than letter units in a language. Simple graphemes will correspond to single letters, and complex

1  
2  
3 graphemes will correspond to letter chunks that map into a single phoneme (e.g., “eau” in  
4  
5 French).

6  
7  
8  
9  
10 **Hierarchical cross-frequency coupling:** measures the interaction between oscillations at  
11 different frequency bands. The main form of CFC in brain oscillations is a phase amplitude  
12 coupling where a hierarchical relation is instantiated so that the phase of low-  
13 frequency rhythm modulates the amplitude of higher-frequency oscillations.  
14  
15

16  
17  
18  
19  
20 **Neural oscillations:** reflect the patterns of rhythmic activity of a neural tissue. Both  
21 individual neuronal activity (spike trains) and interactions between population of neurons  
22 (local field potentials and long-range interactions) are mediated by patterns of rhythmic  
23 activity across a large range of frequency bands. It has been suggested that cognitive  
24 processes depend on patterns of effective, precise and selective interplay between neurons.  
25  
26  
27  
28  
29  
30

31  
32  
33  
34 **Orthographic depth:** refers to the complexity (regularity, consistency) of the mappings  
35 between graphemes and phonemes in a language. In deep orthographies, depending on the  
36 word, one grapheme can map to multiple phonemes and one phoneme can map to multiple  
37 graphemes. On the contrary, in shallow orthographies, these mapping are very regular and  
38 consistent.  
39  
40  
41  
42  
43  
44

45  
46  
47 **Parsing:** refers to the chunking mechanism that will support the selection (delimitation) of  
48 the amount of relevant spatial or temporal information to be attended to by attentional  
49 resources. In our view, it corresponds to parsing mechanisms.  
50  
51  
52  
53  
54

55  
56 **Phase:** The phase of a sinusoidal signal indicates the position of a point in time (instant) on a  
57  
58  
59  
60

1  
2  
3 sinusoidal oscillation. A complete cycle is defined as 360 degrees of phase. Phase can also be  
4  
5 an expression of relative displacement between oscillations (e.g. *neural oscillations*) having  
6  
7 the same frequency. Two oscillators that have the same frequency and no phase difference  
8  
9 are said to be in phase. Two oscillators that have the same frequency and different phases  
10  
11 have a phase difference, and the oscillators are said to be out of phase with each other.  
12  
13

14  
15  
16 **Phase-locking value (PLV):** measures the stability of phase difference between two signals  
17  
18 across time for a specific frequency. For example, PLV can be used to measure the phase  
19  
20 synchronization between the neural oscillations from two separate brain sources across trials.  
21  
22

23  
24  
25 **Phonemes:** correspond to the smallest units of a spoken language that enable distinguishing  
26  
27 between words. It is an abstract linguistic feature as one phoneme can correspond to several  
28  
29 sounds (allophones) depending on speakers' variability.  
30  
31

32  
33  
34 **Sampling:** refers to a screening mechanism of the information falling under the attentional  
35  
36 focus. In our view, it enables the identification and the encoding of sensory information  
37  
38 through attentional focusing.  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60



**Table 1.** Orthographic depth and grain size effects on orthographic development.

		ORTHOGRAPHY	Deep	Shallow
		GRAIN SIZE	Large	Small
Prompted visual	reading	Reading strategy	Lexical reading	Sublexical reading
	oscillations	Parsing	Delta-theta coupling	Theta entrainment
		Focusing	High gamma power	Moderate gamma power
Facilitated situation	Reading development	Expert stages	Early stages	
	Item type	Familiar word	Non familiar word	

## Figure Captions

Figure 1. A. Time (x-axis)-amplitude (y-axis) representation of the French acoustic signal “La dyslexie développementale” (dark blue). The envelope of the speech signal low pass filtered in the delta band (<1 Hz; prosodic information) is represented in green. The envelope band pass filtered in the theta band (4 - 8 Hz; syllabic information) is represented in light blue. B. Possible representation of the hierarchical coupling (with fast oscillations nested in slow oscillations) happening between neural oscillations synchronized to the temporal properties of the speech signal: neural oscillations in the delta and theta bands may respectively support automatic attentional shifting onto prosodic and syllabic information to parse the speech signal and facilitate phonemic encoding reflected in gamma activity.

Figure 2 depicts a qualitative hypothetical scenario for the development of auditory (phonology-related) and visual (orthography-related) oscillatory mechanisms described in the present framework. Skilled readers’ development is represented with plain lines and dyslexic readers’ development with dotted lines. Auditory oscillatory activity is recruited from birth and heavily tuned in response to speech. However, the developmental curve of orthography-related visual oscillations should start growing more drastically with print exposure. Significant gaps between dyslexic and skilled readers on auditory oscillatory functions should be visible before visual oscillatory deficits (see Hood & Conlon, 2004; Lallier et al., 2009). Therefore, we hypothesize that the probability to observe amodal oscillatory deficits increases with the amount of reading experience. Still, atypical visual oscillations could be present from birth in infants with a high risk of developing dyslexia but more difficult to capture with limited orthographic experience. Such hypothesis implies that studies investigating the causal role of visual oscillations in dyslexia should systematically assess reading age matched controls and/or use longitudinal designs (Goswami, 2015a). It is also noteworthy that other types of visual oscillatory activity might contribute to reading

1  
2  
3 acquisition from birth (e.g., gestures and visual speech analysis), but this falls out of the  
4  
5 scope of the present framework.  
6

7  
8 Figure 3. Adapted from the Figure 3 of Goswami and Leong (2013). With permission from  
9  
10 the authors. Spectro-temporal representation of the speech amplitude envelope for the words  
11  
12 "COMfortable" (left) and "deBAtable" (right). The three dominant amplitude modulation  
13  
14 (AM) rates within the envelope are labeled as A (Stress A), B (Syllable AM) and C  
15  
16 (Phoneme AM), and the possible corresponding neural oscillatory frequency ranges are  
17  
18 presented (Delta, Theta and Gamma, respectively). For each subplot, the change in amplitude  
19  
20 (y-axis) over time (x-axis) within each of five frequency bands (z-axis) is shown. High  
21  
22 amplitude is indicated in red, low amplitude is indicated in blue. The modulation pattern of  
23  
24 the Syllable AM (middle row) reveals the 4 syllables contained within each word (numbered  
25  
26 from 1-4). The original acoustic waveform for the word is shown at the bottom in black (D).  
27  
28 The difference in stress patterning between the two words is reflected as a shift in the timing  
29  
30 of the initial peak of the Stress AM toward the stressed syllable (red arrow), and away from  
31  
32 the unstressed syllable (blue arrow). Languages with unpredictable lexical stress like English  
33  
34 would require the sensitive encoding of such timing differences, possibly reflected in slow  
35  
36 neural oscillations (see A. and B.). This would not be necessary for languages with  
37  
38 predictable lexical stress patterns (like French).  
39  
40  
41  
42

43 Figure 4. Illustration of the hypothesis proposing how visual oscillatory processes may be at  
44  
45 play during the early stages of reading acquisition in a shallow orthography (Spanish) and a  
46  
47 deep orthography (English). A. The green arrows represent the eye fixation. Light blue  
48  
49 arrows represent covert attentional shifting. Dark blue circles over words represent attentional  
50  
51 focusing. B. Neural oscillations possibly subtending the processes described in A: delta  
52  
53 oscillations are represented in green, theta oscillations in light blue and gamma activity in  
54  
55 dark blue. C. Possible phonological output resulting from each parsing strategy. In the case of  
56  
57  
58  
59  
60

1  
2  
3 Spanish (1.), attentional shifting mechanisms over words could always rely on letter by letter  
4  
5 sampling, and any parsing mechanisms would lead to accurate phonological decoding. Here,  
6  
7 syllabic parsing is represented as the possible strategy used at the early stages of reading  
8  
9 acquisition (cf Ans, Carbonnel & Valdois, 1998). In English (2. and 3.), parsing mechanisms  
10  
11 are critical for grapheme to phoneme conversion: non optimal parsing strategy (A.2 and B.2)  
12  
13 may lead to inaccurate phonological decoding of the multi-letter grapheme “ea” (C.2). The  
14  
15 optimal reading strategy (3.) would require whole word parsing since the multi-letter  
16  
17 grapheme “ea” may sound differently depending on the word context (e.g., “ready”). Parsing  
18  
19 mechanisms and the coupling between delta and theta oscillations may therefore matter more  
20  
21 for learning to read in deep compared to shallow orthographies. In addition, learning to read  
22  
23 in a deep orthography may encourage the sampling of a greater amount of letters within one  
24  
25 theta cycle compared to shallow orthographies, which would be reflected in higher gamma  
26  
27 power (see B.1. and B.3).  
28  
29  
30

31  
32 Figure 5. A. Illustration of possible causal pathways from oscillatory brain functions, to  
33  
34 cognition, to reading behavior that explains the heterogeneity of dyslexia. The width of the  
35  
36 arrow between Cognition and Behavior levels indicates the putative contribution strength of a  
37  
38 specific cognitive process to word and pseudoword reading. Note that the amodal nature of  
39  
40 the oscillatory-based deficits has yet to be proved at the individual level: if oscillatory-based  
41  
42 deficits are amodal, visuo-spatial attention orienting may be accompanied by prosodic  
43  
44 processing deficits in the same dyslexic individual. Similarly, letter and phoneme analysis  
45  
46 difficulties may be frequently found in the same dyslexic individual. However, we do not  
47  
48 expect visual attention span disorders to be associated with letter and phonemic processing  
49  
50 difficulties (Zoubrinetzky et al., 2016), as they might stem from distinct gamma-related  
51  
52 dysfunction (i.e., the modulation of gamma power by the phase of low-frequency oscillations  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 versus the modulation of gamma power by the phase of alpha oscillations). B. Examples of  
4  
5 possible tasks that could be used to assess the four cognitive clusters described in A.  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For Peer Review

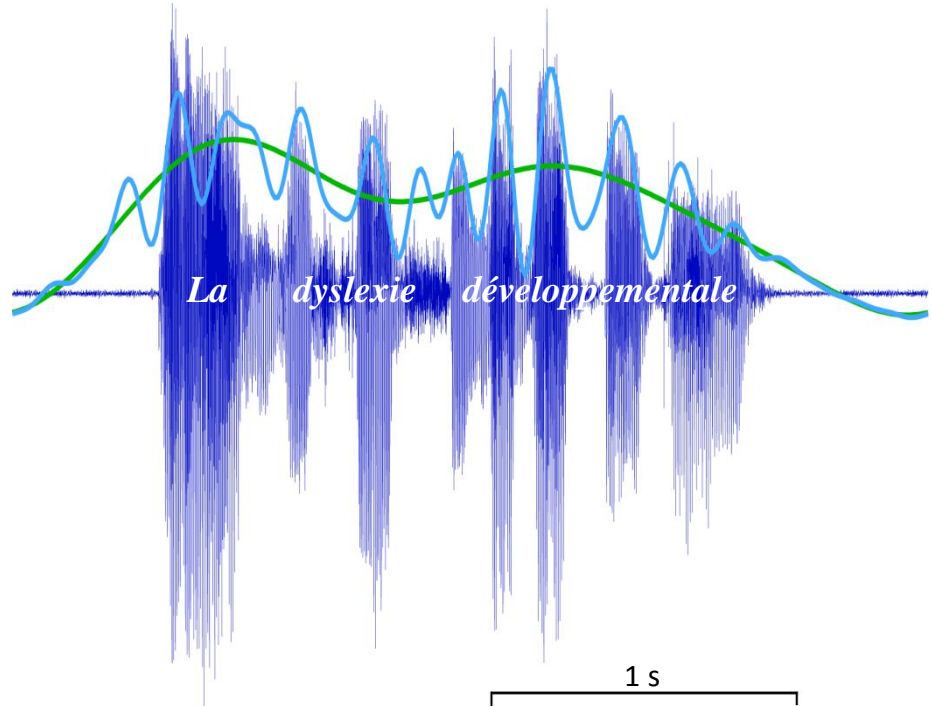
1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42

**A.**

Prosodic AM

Syllabic AM

Acoustic waveform



**B.**

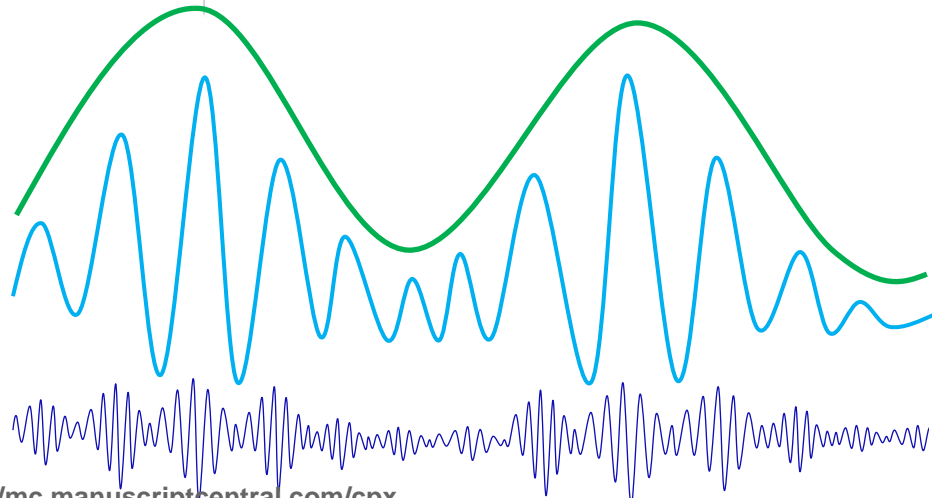
Parsing

Sampling

Delta range (<1 Hz)

Theta range (4-8 Hz)

Gamma range (20-50Hz)



1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43

**Auditory oscillatory activity**  
Phonology-related

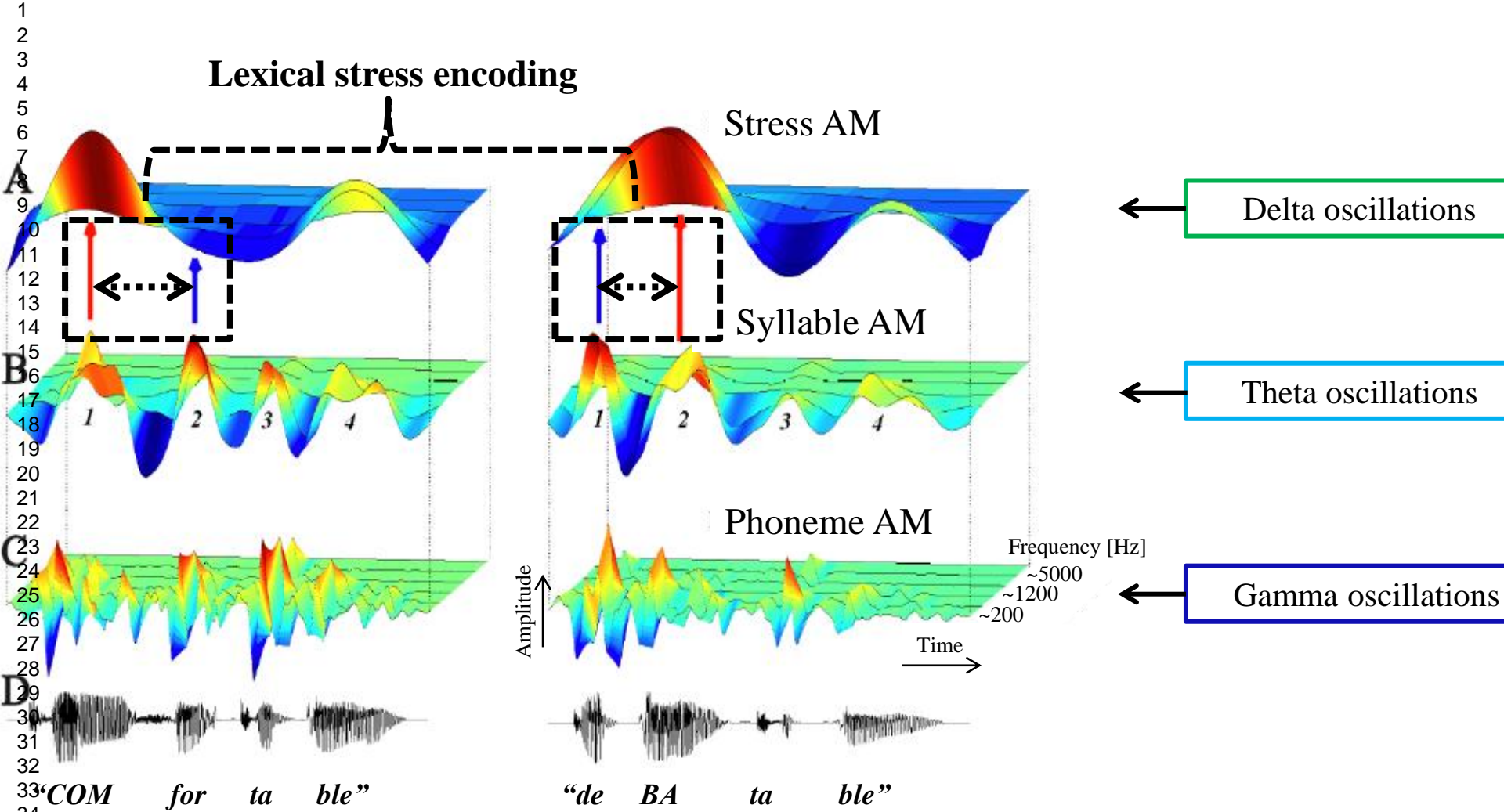
**Visual oscillatory activity**  
Orthography-related



Dyslexia diagnosis

Towards expert reading

Lexical stress encoding





nd  
ifting

2  
3  
4  
hifting

6  
7  
8  
sing

10  
11  
12  
13  
14  
15  
16

17  
range

18  
19  
20  
(Hz)

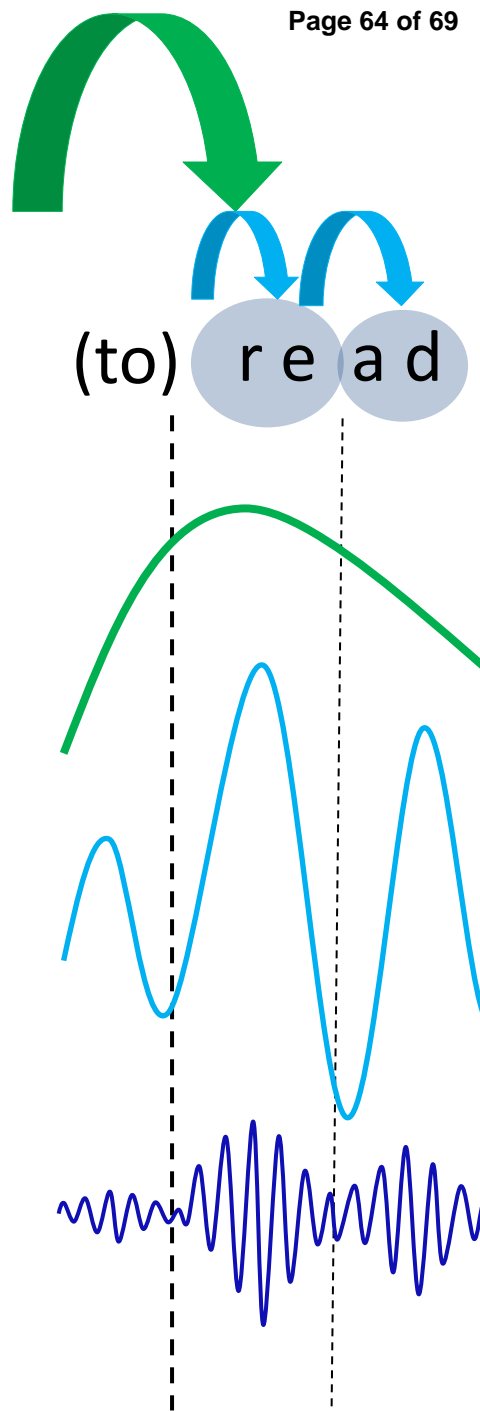
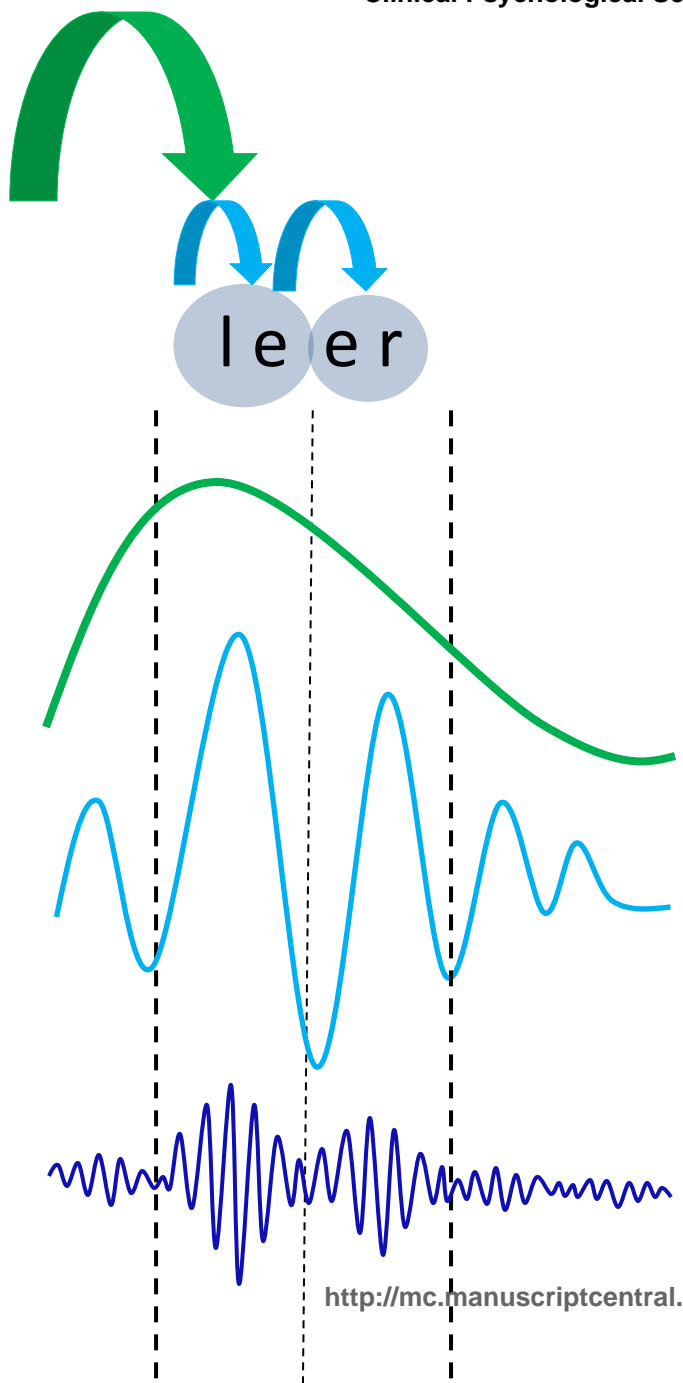
21  
22  
23  
24  
range

25  
26  
27  
28  
(Hz)

29  
30  
31  
32  
33  
range

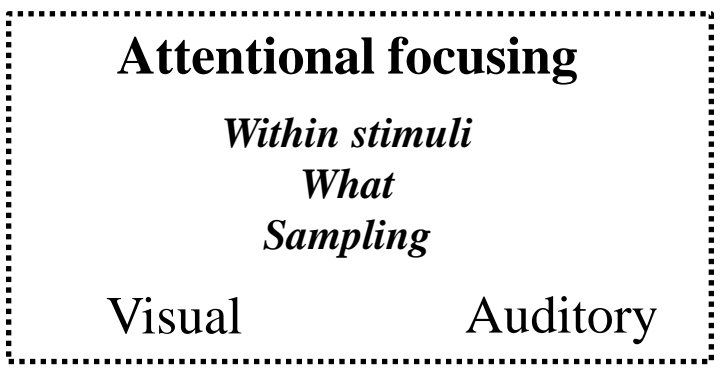
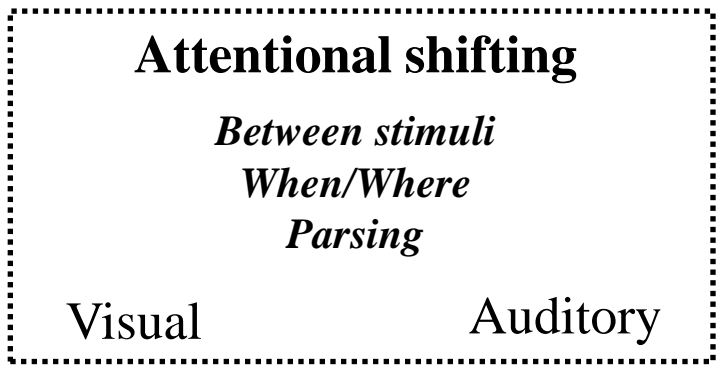
34  
35  
36  
37  
(50Hz)

38  
39  
40  
41  
42  
43



# Oscillatory hierarchical cross-frequency coupling

**Delta** — **Theta** — **Gamma**



Visuo-spatial attention orienting

Phonological analysis (prosody/rhythm)

Visual attention span

Letters & Phonemes analysis

Brain

Cognition

Behavior

**Pseudoword reading**

**Word reading**

<http://mc.manuscriptcentral.com/cpx>

## Glossary

**Amplitude (power):** refers to the magnitude of an oscillation. In neural oscillation, amplitude is interpreted as reflecting the linear summation of the spike trains of neuronal populations whose rhythmic activity can be highly synchronized (eliciting larger amplitude) or desynchronized (lower amplitude).

**Attentional shifting:** reflects a mechanism through which attentional resources are directed to a point in time or space to facilitate the processing of this information. This implies that the allocation of attention to irrelevant information is decreased (inhibition). In the visual modality, overt attentional shifting occurs when the eyes are moving, whereas covert attentional shifting does not and can happen while the eyes remain fixated on a specific point.

**Grain size:** refers to the size of the units that will be relevant for phonological and orthographic information processing. A large grain will correspond to multiple letter/phoneme units whereas small grains may typically correspond to single letter/phoneme. Moreover, grain size will vary depending on the type of orthography (deep or shallow), the reading developmental stage (early or late), or the type of item to be read (e.g., new or familiar word, consistent or inconsistent word).

**Graphemes:** correspond to the smallest units of a written language. These written units correspond to the phonemic oral units. Graphemes better reflect the phonology than letter units in a language. Simple graphemes will correspond to single letters, and

1  
2  
3 complex graphemes will correspond to letter chunks that map into a single phoneme  
4  
5 (e.g., “eau” in French).  
6  
7

8  
9  
10 **Hierarchical cross-frequency coupling:** measures the interaction between oscillations  
11 at different frequency bands. The main form of CFC in brain oscillations is a phase  
12 amplitude coupling where a hierarchical relation is instantiated so that the phase of low-  
13 frequency rhythm modulates the amplitude of higher-frequency oscillations.  
14  
15  
16

17  
18  
19  
20 **Neural oscillations:** reflect the patterns of rhythmic activity of a neural tissue. Both  
21 individual neuronal activity (spike trains) and interactions between population of  
22 neurons (local field potentials and long-range interactions) are mediated by patterns of  
23 rhythmic activity across a large range of frequency bands. It has been suggested that  
24 cognitive processes depend on patterns of effective, precise and selective interplay  
25 between neurons.  
26  
27  
28  
29  
30  
31  
32

33  
34  
35  
36 **Orthographic depth:** refers to the complexity (regularity, consistency) of the mappings  
37 between graphemes and phonemes in a language. In deep orthographies, depending on  
38 the word, one grapheme can map to multiple phonemes and one phoneme can map to  
39 multiple graphemes. On the contrary, in shallow orthographies, these mapping are very  
40 regular and consistent.  
41  
42  
43  
44  
45  
46

47  
48  
49 **Parsing:** refers to the chunking mechanism that will support the selection (delimitation)  
50 of the amount of relevant spatial or temporal information to be attended to by  
51 attentional resources. In our view, it corresponds to parsing mechanisms.  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5 **Phase:** The phase of a sinusoidal signal indicates the position of a point in time (instant)  
6  
7 on a sinusoidal oscillation. A complete cycle is defined as 360 degrees of phase. Phase  
8  
9 can also be an expression of relative displacement between oscillations (e.g. *neural*  
10  
11 *oscillations*) having the same frequency. Two oscillators that have the same frequency  
12  
13 and no phase difference are said to be in phase. Two oscillators that have the same  
14  
15 frequency and different phases have a phase difference, and the oscillators are said to  
16  
17 be out of phase with each other.  
18  
19

20  
21  
22 **Phase-locking value (PLV):** measures the stability of phase difference between to  
23  
24 signals across time for a specific frequency. For example, PLV can be used to measure  
25  
26 the phase synchronization between the neural oscillations from two separate brain  
27  
28 sources across trials.  
29  
30

31  
32  
33 **Phonemes:** correspond to the smallest units of a spoken language that enable  
34  
35 distinguishing between words. It is an abstract linguistic feature as one phoneme can  
36  
37 correspond to several sounds (allophones) depending on speakers' variability.  
38  
39  
40

41  
42 **Phonotactics:** language-specific rules that govern the phonological structure of words  
43  
44 and that constrain the combination of phonemes at the lexical, morphological, and  
45  
46 syntactic levels.  
47  
48

49  
50  
51 **Sampling:** refers to a screening mechanism of the information falling under the  
52  
53 attentional focus. In our view, it enables the identification and the encoding of sensory  
54  
55 information through attentional focusing.  
56  
57  
58  
59  
60

1  
2  
3 **Temporal versus Oscillatory (Time versus Oscillations):** oscillations reflect pseudo-  
4 regular or regular rhythmic fluctuations of sensory inputs or neuronal activity. In  
5 principle, we assume that the notion of time is not tied to any rhythmic dimension and  
6 also encompasses properties of continuous steady signals (like the duration of a  
7 stimulus or the duration of the period during which neural activity across two brain  
8 regions is synchronized). Therefore, oscillations are part of a broader time notion.  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For Peer Review